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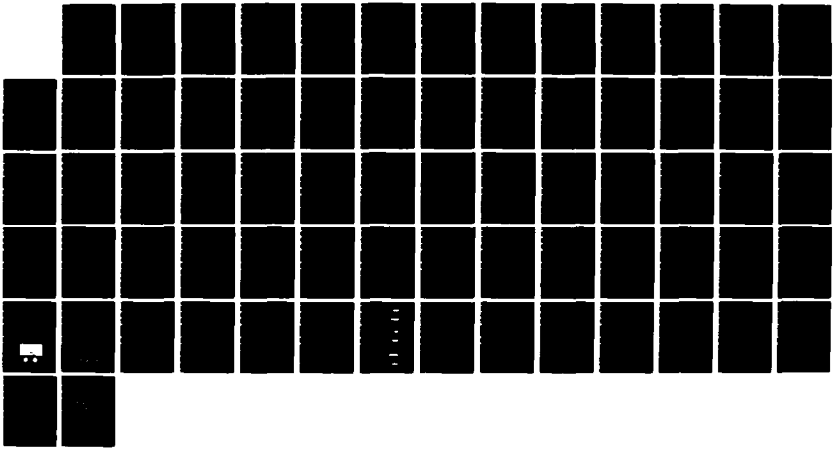

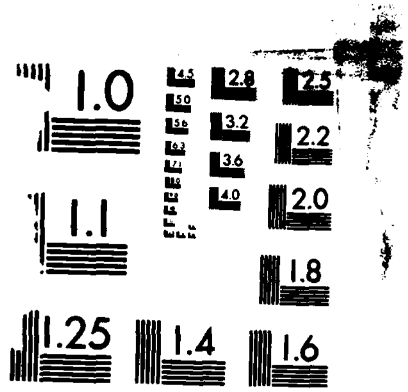

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COMPONENTS OF SPATIAL ABILITY

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FINAL REPORT
GRADUATE SCHOOL OF EDUCATION
UNIVERSITY OF CALIFORNIA
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The goal of this project was to identify information processing components of spatial ability. A summary paper is presented that reviews major psychometric analyses of spatial ability as they relate to theories of information processing. The primary emphasis in the review is of studies isolating individual differences in components of spatial information processing. Research is also reviewed on the acquisition of spatial processing skills. The final section considers implications of this line of research for issues of assessment, particularly as it relates to modern technologies for testing. Keywords

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REPORTS

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Fischer, S., & Pellegrino, J. W. (in press). Hemisphere differences for components of mental rotation. _Brain & Cognition_.

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Components of Spatial Ability

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The goal of this paper is to review advances in the study of individual differences and consider some of their practical implications. We are not concerned with all aspects of human intellect but with the study of spatial ability which constitutes an important subset of research on spatial cognition. There are a variety of reasons for being interested in the study of spatial cognition in general and spatial ability in particular. First, it is of theoretical and practical significance to understand how individuals represent the physical world in which they operate. Evidence exists for a theoretical separation of physical or spatial representations and semantic or conceptual representations. There is also a substantial body of literature suggesting the existence of something called spatial ability which is differentiable from general ability and verbal ability. In addition, there appear to be group differences in spatial ability. For example, males tend to score higher on measures of spatial ability. Finally, measures of spatial ability frequently add unique variance for predicting performance in certain courses such as engineering design or graphics and occupations such as mechanic, architect, or pilot. The preceding is only a cursory list and more will be said about some of these generalizations in the subsequent sections of this paper.

While our general goal is to review research on spatial cognition and spatial ability, our specific goal is to show how an information processing approach to the study of human cognition can facilitate our understanding of individual differences in spatial ability. We will try to show how such an approach has been fruitful for organizing, analyzing and interpreting an extant body of theory and data on spatial ability. To do so we first review psychometric studies of spatial ability. Such a review traces some of the background and history of the concept of a separate "spatial ability." It also serves the purpose of identifying and clarifying some of the confusion surrounding this ability domain with respect to factors, subfactors, and tests. Using Lohman's (1979) reanalysis as a framework, we argue for a set of related spatial factors which can be understood in terms of cognitive processing demands. The organizational framework also leads to certain predictions about sources of individual differences which are substantiated in information processing research.

The second major section of this paper is concerned with theories and models of spatial information processing and their application to the analysis of individual differences in spatial cognition. Such theories and models have been developed apart from psychometric theories of spatial ability, with little or no concern for issues of individual differences. Nevertheless, they provide an analytic framework and a methodology for studying tasks, people and the interaction between the two. In this section we briefly consider Kosslyn's (1980, 1981) theory of mental imagery and applications of this type of theorizing to the study of spatial ability. Our primary focus is on studies of individual differences in components of spatial processing and the relationship to psychometric factors and tests.

Another specific goal of this paper is to show how an information processing perspective leads us to ask questions about the development and acquisition of spatial ability that would not necessarily follow from a psychometric or measurement orientation. In the third major section we review studies of two types indicating substantial absolute changes in people's ability to manipulate "spatial information." One class of studies focuses on age changes in spatial processing while the other class of studies focuses on within individual changes as a function of experience and practice. Results from these studies have interesting implications with respect to views about the modifiability of abilities, the goals of testing, and alternative assessment procedures.

The final section of this paper is a consideration of how the various streams of research can be used address practical concerns. One such concern is the assessment of human abilities, in particular, improvements in assessment that might come about through the use of modern technology. We argue for three things. First, that information processing research allows one to develop more precise indices for the types of processing associated with typical spatial factors. Second, that such research also leads to the generation of new types of tests. Third, that technology makes possible tests of dynamic spatial processing which can contribute to both theory development and practical assessment. Finally, we consider the implications of information processing research with respect to the purposes and uses of testing.

Psychometric Analysis of Spatial Ability

For nearly fifty years the psychometric literature has suggested the concept of a separate spatial ability differentiable from other intellectual abilities such as verbal, quantitative and reasoning ability. Independent of any particular factor theory, it must be conceded that next to a verbal ability factor a distinct spatial factor is the most frequently occurring in the psychometric literature. Paper and pencil tests employing figural-pictorial stimuli have been used since the early 1900's. The original paper and pencil tests were actually drawn versions of wooden performance tests such as form boards, mazes and pegs (Smith, 1964). They were intended as general intelligence tests for persons who had little education or poor verbal expression skills (e.g., United States Army Beta, 1917). However, well before their use as non-verbal intelligence tests, investigators had employed them in studies which showed their importance in predicting success in various trade and engineering courses (e.g., Minnesota Mechanical Assembly Test, 1928; see Likert & Quasha, 1970). The first reported study of the inter-test structure of paper and pencil spatial measures was by El Koussy (1935; cited in Smith, 1964). The author argued for a broad group factor in the correlation matrices which went beyond Spearman's g. El Koussy claimed that it was characterized by the investment of visual imagery in the solution of individual problems.

By 1950, research demonstrating a separate spatial ability was so voluminous that Vernon (1950) proposed a modification of Spearman's theory. Vernon's proposal was for a hierarchical theory that placed two broad group factors between Spearman's apical g and the large number of test specific factors at the bottom. One of the large group factors, v:ed, represents verbal, numerical, reasoning and memory abilities. The other group factor, k:m, represented the complex of spatial-practical-mechanical abilities. These were considered more heterogenous than the v:ed group because they are not solidified and maximized through schooling. According to Vernon, this ability complex was assessed by "mechanical and spatial, physical and manual, and some non-verbal g, perceptual and performance tests" (p. 32). At the time, this represented a major break from the 'two-factor' theory of Spearman.

Major Psychometric Studies

Vernon's theory focuses on the broad group k:m factor but allows for 'minor' spatial factors. By minor, Vernon was referring to the plethora of spatial-like factors identified by American researchers, chiefly, Thurstone and Guilford. Thurstone (1938, 1944) had reported both spatial and perceptual factors while Guilford (Guilford & Lacey, 1947; Guilford, Fruchter & Zimmerman, 1952) reported a perceptual factor along with several spatial factors. By the mid-1950's at least four replicated spatial factors had emerged in the psychometric literature; perceptual speed, spatial relations, spatial orientation and spatial visualization. (Examples of marker tests for these factors are presented in Figures 1-4 and are discussed subsequently.) While all of the relevant research cannot be reviewed, several milestone studies will be reported (for complete reviews see Lohman, 1979; McGee, 1979; Smith, 1964; Vernon, 1961). The focus of the review will be to present the emergence of a contemporary view of spatial abilities.

In Thurstone's (1938) Primary Mental Abilities study, he extracted 13 orthogonal factors from 56 tests administered to several hundred college students. For our discussion only two of the factors are of interest. Thurstone found a large perceptual speed factor, labeled P, which was chiefly defined by his Identical Forms test. Figure 1 contains problems adapted from this test (Identical Pictures; Ekstrom, French & Harman, 1976). The test requires an individual to rapidly find a match for the leading figure among the five alternatives to the right. The author described the factor as representing facility in rapidly perceiving detail. A single spatial factor emerged in the study, labeled S, which had significant loadings for a number of tests including flags, lozenges, cubes, form board, surface development and punched holes. Thurstone characterized his S factor as "facility in spatial and visual imagery (p. 80)." Flags, lozenges and cubes all require the individual to decide if a pair of objects are logically consistent or represent the same side of an object (see Figure 2). In the flags test, examinees are presented with a pair of asymmetric flag drawings in different orientations. The task is to decide if the drawings represent the same side of the flag; the individual must mentally reorient one member of the pair to complete the item. There are several versions of the lozenges test but all use small parallelograms with markings to distinguish front from back and top from bottom. The examinees must decide the location of the markings on a lozenge in a different orientation. A variant of the cubes task (from Ekstrom, French & Harman, 1976) is presented in Figure 2. Each item consists of a pair of cube drawings which have letters on the three visible surfaces. The testee must decide if the two cubes are logically consistent by mentally reorienting one member of the pair. The surface development, punched holes and form board tests (see Figure 4) require much more complex mental transformations of the stimuli for problem solution than the above three tests. In the surface development test a three-dimensional object is presented along with a flat 'unfolded' representation of the object. The individual must mentally fold the flattened object to determine which of its marked edges would coincide with those on the completed object. The punched holes test presents the individual a series of drawings representing the folding of a square piece of paper which is then perforated. The individual's task is to determine the pattern of holes that would be created when the paper is unfolded. The form board test consists of small puzzles. The examinee is given a set of puzzle pieces and a completed outline. The task is to decide if the pieces can be connected to produce the complete outline (for a similar test, see Figure 4).

Guilford and Lacey (1947) edited a volume which summarizes sixteen factor analytic studies comprising the Army Air Forces Aviation Psychology Program (AAF) of World War II. These studies identified a perceptual speed factor (P), two strong spatial factors named Spatial Relations (SR) and Visualization (Vz) along with two more tentative spatial factors (simply, S2 and S3). The P factor was defined by tests requiring the rapid identification of similar stimuli in a spatial array such as airplane silhouettes and arbitrary simple figures as described above. The authors described the factor as involving "the rapid comparison of visual forms (p. 823)". The SR factor was similar to Thurstone's (1938) S factor and was defined by his flags, figures and cards tests which were described above. Other tests used by the AAF researchers that loaded on the SR factor were similar in format but differed in content, using gun, plane and tank silhouettes. The Vz factor was marked by tests similar to Thurstone's surface development and punched holes tests. Guilford and Lacey (1947) say the Vz "factor is strongest in tests that present a stimulus either pictorially or verbally, and in which some manipulation or transformation to another visual arrangement is involved" (p. 838). The S2 factor was identified by only a few tests such as Thurstone's hands where the individual must decide if the hands presented are right or left; thus the factor was characterized as requiring "an appreciation of right-hand-left-hand discrimination" (p. 838; see Figure 3). The S3 factor was later dropped since it was identified in only one of the studies and then by only two psychomotor tests; Two Hand Coordination and Rotary Pursuit.

Guilford, Fruchter and Zimmerman (1952) report the analysis of a large battery of tests administered to over 8000 aviation recruits tested as part of the AAF project but left unanalyzed in the 1947 (Guilford & Lacey) report. Four of the 13 orthogonal factors extracted are important for this discussion. The P (perceptual speed) factor was best defined by Speed of Identification A and C. In form C, parallel strings of arbitrary objects were presented and the examinee's task was to find the matching pairs (Guilford & Lacey, 1947, p. 380). Form A was more complex and utilized drawings of airplanes many of which had been rotated. However, in many cases rotation for correct matching does not seem necessary. Regardless, the two forms defined the factor but much of the form A variance was split off onto the SR factor. The SR factor was marked by some of the same tests as in the 1947 report; Object Identification I and II. Form I was modeled after Thurstone's Flags and Cards but employed silhouettes of guns, tanks, planes, etc. In the test, a standard is presented along with 5 alternatives which are rotated versions of the standard; the individual must pick out the ones that show the same side of the standard. Form II is the second part of the test but employs Thurstone's original flags. A third spatial factor, Spatial Orientation (SO), also emerged in the study and was described by the authors as requiring empathetic involvement where "orientation is with respect to his own body" (p. 55). This factor appears similar to the S2 factor from the 1947 analysis. Among the tests that marked this factor was Visualization of Maneuvers C where the individuals must choose from among five alternatives the correct picture of an airplane following several maneuvers. An important part of this task is that the examinee must make the designated transformations from the pilot's position (i.e., right is relative to the pilot of the pictured plane; see Figure 3). Aerial Orientation also defined SO. In this test the individual is given a cockpit view of a shoreline and must use this to choose from among 5 alternatives the correct photograph of a shoreline with an airplane above (see Figure 3). The final factor of importance in the study was the Vz factor. The factor was defined by a complicated version of Thurstone's punched holes test called Visualization I. The other reference test was Visualization II which required the examinee to read a description of a solid cube that was painted different colors on each face and then cut into smaller blocks. The testee was then to determine the number of blocks with varying color combinations (e.g., how many blocks with 1 blue and 1 red surface?). Overall, these factors converge well with those reported in the 1947 summary.

The SR and Vz factors identified in the Guilford and Lacey (1947) and Guilford et al. (1952) studies appear to represent a partitioning of Thurstone's S factor. To bolster the validity of the earlier analyses, Zimmerman (1953) reanalyzed Thurstone's PMA battery utilizing newer factor rotation methods. The reanalysis showed two orthogonal spatial factors instead of the single S factor originally reported. The first factor, SR, was similar to Thurstone's and defined by flags, lozenges and cubes. The second factor, Vz, was defined principally by the punched holes and form board tests although all of the spatial tests had positive loadings on both factors. Zimmerman (1953) describes the difference between the two factors in terms of item and transformational complexity. The simpler SR factor tests require quick comparison and mental rotation or empathetic involvement while the more complex visualization problems, requiring many transformations, evokes a detailed mental representation that can be operated on. Zimmerman (1953) suggested that the two factors may actually represent a break in a continuum. Indeed, another reanalysis by Lohman (1979) supports this notion by showing that the two factor solution (SR and Vz) was appropriate but that the factors should be allowed to correlate (the actual correlation was .64).

Zimmerman (1954a), following his extensive experience with the AAF studies, published a more formal and general restatement of his earlier (1953) hypothesis concerning the nature of the spatial factors. He argued that the factor composition of spatial tests was a function of item complexity. Specifically, he proposed that as problem complexity increased the test should respectively emphasize perceptual speed, spatial relations, visualization and reasoning. This hypothesis is partially supported by the separation of the SR and Vz factors in the reanalysis of the PMA correlation matrix. The more complex tests, surface development, punched holes and form board, split off and defined the Vz factor. The item complexity hypothesis was explicitly tested by Zimmerman (1954b) utilizing three versions of the Visualization of Maneuvers test developed for the AAF. The test showed the silhouette of an aircraft followed by a description of either one, two or three maneuvers (e.g., bank 90 degrees right). The individual's task was to select from among 5 alternative silhouettes the one showing the correct final orientation. Figure 4 contains an example of the more difficult three transformation problems. The hypothesis was mostly supported. He successfully demonstrated that the three versions of the test fell on different factors; the test with one transformation loaded mostly on P, the two maneuver version loaded mostly on SR but some variance was split onto Vz, the three transformation test loaded solely on Vz. However, Zimmerman failed to show the hypothesized saturation on a reasoning factor.

A Contemporary Reanalysis

Lohman (1979) reanalyzed the spatial test submatrices from many of the largest and most influential aptitude studies conducted in the United States. The purpose of the project was to organize under a common theoretical and methodological umbrella the multitude of published factor analytic studies. The theoretical view was that abilities are best viewed in a hierarchical structure such as Vernon's (1950, 1961) and Cattell's (1971). The methodological approach was to look for convergent interpretations from a uniform hierarchical factor analysis assisted by cluster analysis and multidimensional scaling. The reanalysis concludes that, along with the perceptual speed factor, three spatial factors are consistently supported by the available data. The factors are Spatial Relations, Spatial Orientation and Visualization. The factors can be described by their marker tests, as in Figures 1 through 4, and the similarities of the global mental processes which appear to be used for item solution (see Carroll, 1976 for a similar type of analysis). The perceptual speed tasks appear to demand very rapid encoding and comparison of relatively simple stimuli such as letters, numbers and nonsense figures. Spatial relations problems also require fairly rapid encoding and comparison processes but they additionally require that alternatives be mentally rotated into congruence with the test standard. The spatial orientation tests are more diverse but they all appear to tap the underlying ability to imagine a stimulus array from a different perspective by encoding the various orientation dimensions (e.g., bank, pitch, heading) or positions and then translating them to alternative perspectives. The factor is sometimes difficult to identify since certain problems allow individuals to either imagine an alternate viewing position or mentally rotate the entire array (this would be a SR solution). The last factor, visualization, is represented by a wide variety of tests, but they seem to share two important features: they tend to be relatively unspeeded and are more complex than tests which load on the other factors (p. 127).

Lohman (1979) concludes that these factors can actually be described as representing two correlated dimensions. One dimension is speed-power and the other is a simple-complex dimension. Using a hierarchical representation which is shown in Figure 5, the Vz factor abstraction is at the top with tests below it arranged horizontally with perceptual speed at one end and mental rotation tests at the other. The vertical axis is the speed-power dimension while the horizontal axis represents the simple-complex dimension. Tests can then be located in this positive manifold with the lower left corner representing the most simple and speeded of all possible spatial tests. This same representation can been used to describe the mental processes and processing demands of the tests in much the same way. The origin of the quadrant represents very rapid and simple matching operations. Movement upward and away from the origin represents increases in the number and/or complexity of the processes involved. More will be said concerning the processes underlying spatial task performance in the next section.

Predictive Validity

Before considering the cognitive processes underlying performance on the types of tasks illustrated in Figures 1-4, let us briefly digress to emphasize why we might be interested in this area of intellectual ability. The effective use of spatial information is one aspect of human cognition and it is manifest in situations ranging from navigating through one's environment to determining the trajectories of approaching objects. These skills are also required in intellectual endeavors ranging from solving problems in engineering and design to physics and mathematics. As stated earlier, spatial tests have a long history of consistent predictive association with a variety of criteria. Smith (1964; see also McGee, 1979) provides an extensive review of the predictive validity of spatial tests. These tests are correlated with many academic courses which are unrelated to general and verbal intelligence tests. Smith (1948; cited from Smith, 1964) administered a variety of spatial and intelligence tests to first and second year secondary school students. The spatial test battery was predictive of engineering drawing ($R = .66$) and art ($R = .39$) while the Otis Intelligence Test produced correlations of -.07 and .19, respectively. Smith also reports a validity study by Holzinger and Swineford (1946) which shows that spatial tests are unrelated to foreign language (-.06), biology (-.00) and English (.00) but strongly related to drawing (.69), shop performance (.46) and geometry (.23). The Manual for the Differential Aptitude Test (Bennett, Seashore & Wesman, 1974) reports several hundred validity coefficients between academic achievement and the DAT spatial subtest. The highest correlations (in the .60's) were obtained with tests of geometry, math, quantitative thinking and map reading while the lowest correlations (near .10) were with spelling, writing and social science.

The validity of spatial tests has also been extensively demonstrated with technical training and occupational success. The AAF studies by Guilford and

Lacey (1947) were directed to evaluate the validity of a variety of tests in predicting the performance of pilots, bombardiers and navigators. The validity coefficients for the spatial tests were among the highest in all three occupations (the values ranged from near zero to as high as .7). The manual for the Revised Minnesota Paper Form Board (Likert & Quasha, 1970), an adaptation of one of the oldest paper and pencil spatial tests, reports over 100 validity coefficients with various technical school courses and job success. The criteria employed in these studies were quite diverse, ranging from auto mechanics (.37), baking (.29), detail drafting grades (.48), electrical circuit design (.52), topography (.53), dentistry techniques (.24), pharmaceutical packing inspectors (.57), bricklaying performance (.38) and power sewing machine work quality (.32). This presentation makes it quite clear that the abilities assessed by paper and pencil spatial tests are important to successful performance in a variety of academic and occupational categories and are therefore worthy objects of more detailed research into the cognitive processes which underlie test performance.

Information Processing and Individual Differences

Given the importance of spatial ability as a major aspect of intellectual ability, and the wide variation among individuals, how might we understand this aspect of cognition? By understanding we mean the mechanisms associated with processing spatial information, those mechanisms associated with individual differences, the changes in processing associated with experience or practice, and finally, the modifiability of such skills. To address these issues we must look to another well developed body of research and theory on spatial cognition.

A Theory of Spatial Cognition

Cognitive psychologists have vigorously pursued issues in spatial information processing. As a result of these efforts we now have a reasonably well developed theory of the cognitive structures and processes that underlie the solution of a wide range of spatial problems, including those found on standardized tests of spatial ability. For purposes of discussion, we will briefly focus on the elaborate theory developed by Kosslyn (1981). His theory evolved from an extensive program of research on the processing of mental images. Although it is conceived as a theory of mental imagery, it is also applicable to issues concerning the processing of visual stimuli. A central aspect of this theory is the idea that the human mind creates and operates on analogical representations that preserve spatial properties of visual stimuli. The theory distinguishes between structures and processes. There are two types of structures. One is a visual buffer or short term memory. This medium mimics a coordinate space and it supports data structures that depict information. Regions of the buffer are activated and these regions correspond to portions of depicted objects. Relations among activated portions mirror actual physical relations of the object or objects depicted. The visual image or representation resides in the visual buffer and such a representation is derived either from actual visual input or from information stored in long term memory. Properties of this medium are especially important and these include resolution and spatial extent. The other major structures in the theory are the types of information stored in long-term memory. This includes both propositional information about the parts of objects and their relations, and information about the literal appearance of an object.

Kosslyn postulates a set of processes that operate on the various structures just described. For present purposes we will focus on those processes that operate on the visual buffer. One major process is Regenerate which refreshes or reactivates the representation which fades over time. If a representation is to be operated on then it must be maintained over time and Regenerate is the mechanism for doing so. Of particular significance are the processes for operating on visual representations for the purpose of transforming them. Several specific transformation processes are postulated and these include Rotate, Scan, Pan, Zoom, and Translate. Each of these processes involves some manipulation of the representation resulting in a modification of the representation in the visual buffer. Finally, there are processes that inspect and classify patterns depicted in the representation. These include a Find and Resolution process.

The structures and processes in Kosslyn's theory work together and their interaction is modeled within a computer simulation program. The purpose of the simulation is to test the sufficiency of these assumptions for mimicing results obtained in a variety of studies on the processing of visual images. Suffice it to say that he has been successful in simulating a wide range of empirical results. He has also used his theory to derive additional predictions about human performance which were subsequently verified.

Applicability of the Theory

Kosslyn's theory is an attempt to address one of the major issues raised earlier in this section, specifically, what are the mechanisms underlying specific intellectual performances. The performances of interest are the manipulation of simple and complex visual representations for the purposes of making decisions or solving problems. There are several ways in which we can use his theory to discuss issues about this domain of intellectual ability. First, it emphasizes the fact that the processing of visual-spatial information is composed of many basic processes that interact with information representations. Second, tasks or performances can vary on several dimensions. One such dimension is the number of processes that must be executed to achieve a given result. Another dimension is the types of processes necessary to achieve that result. Third, individuals can vary in their performance depending upon how well they execute certain processes and the extent to which these processes are necessary for solving different types of problems.

A theory of spatial information processing, such as Kosslyn's theory, not only addresses issues concerning the mechanism's underlying this class of intellectual performance, but it also provides a basis for understanding issues associated with individual variation within this intellectual ability domain. We have a framework for simultaneously analyzing differences among individuals and tasks and for understanding psychometric data on spatial ability.

There are three ways in which information processing theories and models have been used to study issues of individual differences in visual-spatial processing. One way is to initially ignore psychometric indices and to deal with individual differences entirely within the context of the Kosslyn theory of mental imagery. In this approach, the theory is not really used to study issues of individual differences, rather, individual differences are used to test implications of the theory. Kosslyn, Brunn, Cave and Wallach (1983) conducted a study representing such an effort. It was designed to do two things: (1) determine if imagery ability was general and "undifferentiated" or, as suggested by his theory, a collection of separate abilities which can vary independently, and (2) to use an individual differences approach to verify the psychological validity of the components specified in the theory. They used a series of imagery tasks designed to tap various components in his theory. For each task, they postulated an information processing model representing the specific processes required for performing that task. The tasks included image rotation, image generation, image inspection, and image reorganization. A total of eight tasks were used and eleven performance measures were derived from these eight tasks. The tasks were administered to a random sample of 50 adults ranging in age from 17 to 48 years old.

The results of this study supported two conclusions. First, imagery ability is not general and undifferentiated but rather is composed of several elements corresponding to components of the imagery theory. Correlations among performance measures varied substantially and the pattern was generally consistent with assumptions about the imagery components contributing to a particular performance measure. Second, the theory predicted the observed correlations among task performance measures and provided a framework for interpreting the results of cluster and factor analyses.

The Kosslyn et al. (1983) study is one example of linking information processing theories to issues concerning individual differences. It supports the idea that individuals vary in their specific abilities and that tasks vary in the extent to which they call upon these abilities. What Kosslyn et al. (1983) have not done is provide a link between their theory and traditional measures of spatial ability such as those described earlier.

A second way of linking an information processing theory with the analysis of individual differences is to go one step beyond the Kosslyn et al. (1983) study and show how the components of the imagery theory are related to each other and to traditional measures of spatial ability. Such an effort was pursued by Poltrock and Brown (1984). The starting point for their study is Kosslyn's theory of the structures and processes associated with imagery. The theory suggests several potential sources of individual differences in spatial processing ability. Two major sources of individual differences can be the properties of the visual buffer and the efficiency of the processes that operate on information contained in this medium. Poltrock and Brown used several imagery and spatial processing tasks designed to tap various separate capacities. The tasks were administered to a group of 77 adults who varied in spatial ability as measured by standardized reference tests.

Poltrock and Brown analyzed the relationships among 15 performance measures derived from six separate tasks. They then derived nine measures of imagery or spatial processing ability which are indicated in the left hand portion of Figure 6. Each measure corresponds to one or more functions in the Kosslyn imagery theory. In addition to obtaining measures of imagery functions, Poltrock and Brown administered a battery of spatial ability tests. The labels for these tests are indicated in the right hand portion of Figure 6. An analysis of the correlations among these tests suggested a single general spatial factor that they have labeled visualization (after Cattell, 1971). The entire figure represents a model constructed to test the hypothesis that the visualization factor reflects, in part, an ability to use imagery. The righthand side of this model represents a single factor principal axis factor model. The lefthand side specifies that visualization ability is composed of a linear combination or correlated cognitive imagery measures. According to this model, the cognitive imagery measures are unrelated to performance on each spatial ability test except through the influence of visualization ability. Confirmatory factor analysis techniques were used to verify this type of model. Six of nine path coefficients for links between imagery measures and visualization ability were significant. The strongest direct connection was between visualization ability and an accuracy score presumed to measure buffer capacity. Other direct links indicate that visualization ability is associated with the efficiency of specific functions such as rotation and integration.

The Poltrock and Brown study represents a major attempt to link information processing theories to psychometric test data. Like Kosslyn et al. (1983) it supports several assumptions. First, that imagery and spatial processing involve separable components, second, that individuals vary in these component functions, and third, that tasks vary in the functions necessary for performance. However, Poltrock and Brown have also shown that these separate functions combine to produce a general ability construct referred to as spatial visualization which is assessed by a wide range of standardized tests.

The research described thus far leads us to a better understanding of one complicated aspect of human cognition and the ways in which individuals may vary in their capacities to solve spatial problems. What we have yet to demonstrate is how differences in specific information processing capacities are manifest in actual measures of spatial ability. We have an indirect link between cognitive processing measures and performance on tests representing spatial ability.

The third way of linking an information processing theory to psychometric tasks and data is to use it as a basis for rational and empirical task analysis. This is sometimes referred to as a cognitive components approach to the analysis of individual differences (Pellegrino & Glaser, 1979; Sternberg, 1977). The essential elements of this approach are as follows. First, a task or set of tasks denoting a specific ability is analyzed from an information processing perspective. This analysis involves specifying one or more information processing models for task performance. The processes specified within the model are derived from a general theory, of which Kosslyn's imagery theory is one example. Systematic problems are designed to provide an empirical test of the model. The model testing also provides mechanisms for deriving estimates of the time and/or accuracy of executing individual processes. These estimates can then be used to examine the component processes contributing to individual differences in the task or tasks of interest.

Earlier, we indicated that spatial ability can be broken down into at least three separate factors and that these factors seem to vary on two dimensions. One was the speed-power dimension and the other was a complexity dimension. We can treat these dimensions as hypotheses about what we would expect to find as the major sources of individual differences in tasks sampled from these continua. More specifically, we would expect that individual differences in perceptual speed and simple spatial relations tasks would be primarily associated with measures of processing speed while individual differences in complex spatial relations and spatial visualization tasks would reflect an increasing contribution of processing accuracy. Similarly, we would expect that the models for describing task performance would reflect a larger number of component operations and/or more executions of individual processes.

These predictions will be easier to understand if we briefly reconsider each of the spatial factors and their associated tasks. Perceptual speed tests have the following generic characteristics: (1) the stimuli are simple, consisting of alphanumerics or simple geometric figures, and (2) there is either a comparison of stimuli to determine if they physically match or a search through an array for the presence of a physical target. Speed of making comparisons rather than accuracy is the basis of differentiation given the brief time limits and the simplicity of the stimuli. In information processing terms, only encoding, comparison and response components are required for problem solution. Spatial relations tests have the following generic characteristics: (1) the stimuli are unfamiliar two- or three dimensional shapes or structures and (2) there is a comparison of stimuli in different orientations to determine if they physically match. Individual differences can be a function of both speed and accuracy of process execution and this will vary with properties of the stimuli such as complexity and dimensionality. The latter affect the certainty of difference detection and also interact with structural characteristics such as capacity and quality of representation. In information processing terms, basic encoding, comparison and response processes are required for problem solution as well as rotation or transformation processes. Spatial visualization tasks are far more heterogeneous. They do, however, have the following characteristics: (1) the stimuli are multiple element two- or three-dimensional shapes and (2) there is a comparison of the physical match of folded and unfolded objects or completed objects and sets of pieces. Individual differences are more likely to be associated with accuracy rather than speed since multiple processes need to be executed and coordinated, with these operations performed on complex representations that tax representational capacity. There is also a possibility of strategic differences in problem solution. The processes required for solution include encoding, comparison, response, search, rotation, and other transformations.

The correlation between performance on tasks representing the same or different factors should be a product of the commonality of the processes required for problem solution, the relative significance of each process to overall solution, the type and amount of "data" submitted to the process, and process interactions with structural capacity and strategies. On this basis, one expects tests of perceptual speed to correlate more highly with simple spatial relations tests than spatial visualization tests. Spatial relations tests should have moderate correlations with both perceptual speed and spatial visualization tests. We and others have found this to be the case and it emphasizes the idea that the dividing line between "spatial" factors must always be somewhat arbitrary since how performances correlate will depend on the cognitive processes, structures and strategies contributing to the performances, not the factors. From an empirical and theoretical standpoint, we can use this type of approach to analyze (1) relationships among spatial processing tasks, as was done by Kosslyn et al. (1983), and/or (2) sources of individual differences in performance on tasks associated with various spatial factors. In the following brief sections we review the results of studies focusing on sources of individual differences in perceptual speed, spatial relations and spatial visualization tasks.

Perceptual Speed

In the preceding section we noted that tests of perceptual speed can be characterized as requiring three basic cognitive processes: encoding, comparison and response. We do not know how and how much each of the these processes contributes to overall individual differences on standardized instruments. To address this issue we have used two tasks that permit a systematic decomposition of performance. In one task, the individual is presented pairs of matrices containing 3, 5, 7 or 9 alphanumerics. The task is to determine if the matrices are the same or different. By varying the number of elements in the matrices and the degree of difference (1, 2 or all mismatching elements) we can test various models of performance while simultaneously estimating three components of processing: (a) time for a single encoding and comparison, (b) motor response time, and (c) additional time for a "different" response. The second task we have used is visual search for an unfamiliar symbol in an array of fifteen symbols. On each trial, the individual is presented a target stimulus for a brief interval and then shown the array. The task is to make one response when the target is found in the array and another response if it is not present. Response time is a linear function of target position and thus we estimate two components of processing: (a) time for a single encoding and comparison and (b) motor response time.

We have used these two tasks with two separate groups of individuals (N=60 in each group) who varied in several cognitive abilities as determined by a battery of reference ability tests. In each study the processing components were estimated for each individual and correlated with reference ability scores. In the matrix comparison task, the measure of encoding and comparison speed correlated -.48 (p < .001) with perceptual speed scores while the measure of response speed showed a -.32 (p < .05) correlation with perceptual speed. The time to respond different was uncorrelated with perceptual speed. None of the measures are correlated with the other reference abilities. In the visual search task only the measure of encoding and comparison speed had a significant simple correlation (r = -.32, p < .05) with perceptual speed. However, a multiple regression analysis indicated that both measures of processing speed significantly contributed to the prediction of perceptual speed ability, with encoding and comparison speed the more important predictor. Thus, in both tasks, results are obtained supportive of the hypothesis that measures of perceptual speed can be decomposed into processing components and that individual differences are a function of the speed of executing encoding-comparison operations as well as motor responses. The latter, however, is less important than the former.

Spatial Relations

We and others have also analyzed sources of individual differences in spatial relations ability. In one study, we focused on spatial relations ability as measured by Thurstone's Primary Mental Abilities (PMA) space test (Mumaw, Pellegrino, Kail and Carter, 1984). The PMA test contains two dimensional stimuli and each problem requires identification of stimuli that are identical to a standard following rotation in the picture plane. Problems from this test were illustrated earlier. To study performance in this type of task we drew upon the information processing model developed by Cooper and

Shepard (1973). Pairs of stimuli which were either familiar alphanumerics or unfamiliar characters drawn from the PMA test were presented on individual trials. When problems such as these are presented, the typical result is a linear relationship between overall solution time and the angular disparity between the two stimuli in the pair (see Figure 8). The model for performance includes several processes. Measures of the speed of executing these processes are derived from the linear function relating reaction time to angular disparity. The slope of the linear function reflects rotation rate and the intercept reflects the time for encoding, comparison and response processes. A large number of young adults were tested on problems of this type. For each individual, four measures of performance were derived: two intercept measures and two slope measures reflecting performance on each class of stimuli. Figure 7 shows data for the intercept measures as a function of spatial ability scores on the Primary Mental Abilities test. As can be seen in this figure, there are minimal ability differences in the speed of encoding, comparing and responding to familiar alphanumeric stimuli. There are, however, ability differences in encoding and comparing unfamiliar stimuli. This figure also shows data for the two slope measures, again plotted with respect to spatial ability. There are substantial ability differences in the speed of performing the rotation process and these differences are larger for the unfamiliar stimuli. We failed to observe any substantial ability differences in the accuracy of solving such problems. Correlational analyses confirmed that individual differences in reference test performance were predicted only by differences in the speed of process execution.

In another study (Pellegrino & Mumaw, 1980), we pursued a similar analysis of individual differences in spatial relations performance with more complex stimuli involving three dimensional mental rotation. Differences in the speed of solving two versus three dimensional mental rotation problems are illustrated in Figure 8. As can be seen in this figure, both types of stimuli produce linear reaction time functions but the slopes and intercepts are considerably higher for the three dimensional rotation problems. In addition, individuals tend to be more error prone in solving three dimensional rotation problems. In this study, we presented a large number of problems to individuals varying in spatial ability as determined by a reference test requiring complex mental rotation. Again, we derived various measures of processing speed and accuracy. The left panel of Figure 9 shows intercept data contrasting individuals in the top and bottom quartiles of ability on the reference test. There are substantial ability differences, particularly with respect to the speed of making different judgments. The center panel of this figure shows similar data for the slope measures. Both slope measures show substantial ability differences in the speed of executing processes associated with the rotation of three dimensional objects. The right panel of the figure shows similar data for solution accuracy. Unlike two dimensional rotation problems, there are also ability differences in the accuracy of solving these problems.

Before discussing similar analyses of spatial visualization tasks, we should summarize the results described thus far. In the case of performance on simple spatial relations tasks, the results are consistent in showing substantial speed differences in the encoding and comparison of unfamiliar stimuli and in the execution of a mental rotation or transformation process that operates on the internal stimulus representation. The differences in encoding, comparison and rotation processes that exist for simple spatial relations tasks are of even greater magnitude in complex spatial relations tasks (see also Egan, 1978; Just & Carpenter, in press; Lansman, 1981). The complexity of stimuli such as the Shepard and Metzler block figures leads to substantial errors on these problems which are also related to individual differences. The particular errors that seem most important for differentiating among individuals involve the processes associated with determining that two stimuli are non-identical.

Spatial Visualization

When we move to spatial visualization tasks, we expect that individual differences in performance will be a combination of speed, accuracy, and perhaps strategy for task execution. Two studies that we have conducted support this expectation. One visualization task that we studied is known as a form board and was illustrated earlier in Figure 4. To study the processes underlying performance on this task, we developed a systematic problem set and task variant (Mumaw & Pellegrino, 1984). The types of problems used are shown in Figure 10 and they systematically vary in process complexity. Problems such as these were used to test an information processing model as well as to study individual differences in process execution. Performance in this task was a systematic function of problem type and complexity. As shown in the top panel of Figure 11 the time for problem solution increases as more processes are required and as each required process must be re-executed for each new problem element. Not only does solution time increase with problem complexity but errors also show a similar increase. As shown in this figure, there were systematic latency differences between high and low ability individuals. The top two panels show performance on problems where the individual pieces corresponded to the completed puzzle. As problem complexity increased, ability differences in solution time also increased. This was also reflected in correlations based on measures of processing speed derived from fitting the information processing model to the data of individual subjects.

The bottom two panels show performance differences on problems where there was a total mismatch between the completed puzzle and the individual pieces. High ability individuals were very fast in detecting these mismatches while low ability individuals were exceeding slow. Not only did individuals differ in the speed of detecting differences but they differed substantially in the accuracy of doing so. Individual differences in this visualization task were predicted by a combination of both speed of processing and accuracy of processing measures. However, the accuracy measures made a more substantial contribution to the prediction of individual differences in ability level.

The last task we will discuss is another visualization task generally known as surface development. In our variant of this task, the individual is presented a flat, unfolded representation of a cube with two or three surfaces shaded. The task is to determine the relationships among the shaded surfaces when the cube is constructed. We can specify a general model for this type of task and demonstrate that the time to determine the relationships among the shaded surfaces is a function of the minimum number of folds necessary to establish their relative positions (Shepard & Feng, 1972). We have used problems of this type to analyze individual differences in spatial visualization ability (Alderton & Pellegrino, 1984). Ability differences were not associated with speed of solving these problems, in fact the correlation between mean response latency and reference test scores was practically zero. Ability differences were associated with the accuracy of solving problems and high ability individuals could solve problems involving more complex folding sequences. A closer look at our latency data revealed an interesting difference between our high and low ability individuals and helped explain why mean solution time was unrelated to ability. Figure 12 shows the relationship between problem solution time and problem complexity. The high ability individuals showed a very systematic latency pattern. Problem solution time increased with each additional surface to be manipulated for final solution. In contrast, the low ability individuals showed a much less systematic latency pattern suggesting an erratic solution procedure and/or a breakdown in the ability to coordinate the image beyond a certain level of complexity. The erratic latency pattern coincides with their lower overall accuracy of solution.

Conclusions

We can summarize the implications of these studies of perceptual speed, spatial relations and visualization performance and the relationship to Kosslyn's and Poltrock and Brown's research. Individual differences data obtained from several simple and complex spatial processing tasks can be considered together to formulate a preliminary answer to the question of what constitutes spatial aptitude. By looking across tasks, one might initially conclude that spatial aptitude is a function of several capacities including the ability to establish precise and stable representations of unfamiliar visual stimuli. Such representations can then be operated on or transformed with minimal information loss or degradation. It appears that individuals high in spatial aptitude are faster at representing unfamiliar visual stimuli and what is ultimately represented is more precise. Differences in the quality of representation may also give rise to other speed differences such as the superior rotation and search rates observed in different tasks. Problems of representation are most apparent in the more complex tasks that require the representation and manipulation of stimuli having several interrelated elements. If we assume that stimulus representation and processing involve a visual short term memory or buffer, then skill differences may also be a function of capacity and resolution within this system. Differences between spatial relations and visualization tasks may partially reflect a difference in the importance of coding versus transformation processes within this system. Another difference between the two factors appears to involve single versus multiple transformations and the coordination and monitoring of the latter.

All three illustrations of linking information processing research with individual differences emphasize the relevance and importance of trying to relate dimensions of variation in human performance with theories and models of the mechanisms underlying a given intellectual performance. Our understanding of intellectual ability, and spatial ability in particular, is enhanced by considering simultaneously the dimensions of variation in solving spatial problems and the mechanisms responsible for performance and performance variation.

Acquisition of Spatial Processing Skill

We know that there are reliable individual differences in spatial ability. We also know that such differences are partially attributable to the speed and accuracy of executing specific mental processes. It is not uncommon to view such aptitude differences as relatively stable characteristics of individuals and populations. Standard testing procedures tell us that if we re-administer psychometric tests then the test-retest correlations will be high, .75 or above for any respectable ability test. In addition, absolute scores will not change greatly. An individual's scores may go up or down by a few points reflecting regression to the mean. Such data are often interpreted as an indication that ability differences represent immutable characteristics of individuals and that they are relatively fixed.

Another basis for a psychometric belief in the stability of intellectual abilities comes from longitudinal research projects in which individuals are administered tests for several years in succession. In these cases, one can compute correlations between intelligence as an adult and intelligence at various points earlier in development. In fact, test scores obtained from infancy typically are poorly correlated with adult intelligence. However, beginning in the preschool years the correlations are statistically significant and by the elementary school years they are quite large.

Ignored here is the fact that stability and change can have two meanings. One meaning refers to the relative level of performance and the other refers to absolute level of performance. Data from longitudinal studies typically reflect stability in individuals' performance relative to each other while disregarding any absolute changes such as all individuals being able to solve more problems or more difficult problems. Data from test-retest reliability studies reflect stability in both relative and absolute performance but without any intervening experience that might be expected to produce a general or differential change in absolute performance.

Our view of intellectual abilities may be distorted by psychometric data suggesting both relative and absolute stability of such abilities. A different view of intellectual abilities is suggested by research combining developmental and information processing approaches. Anyone who has been involved in developmental research, or who has been a parent, knows the changing capabilities of children at different ages. These developing capabilities can be documented for specific intellectual functions such as those associated with spatial information processing. Figure 13 is an illustration of developmental changes in one aspect of spatial processing. These data are from a study conducted by Rob Kail on the development of rotation speed (Kail, 1983). Rate of rotation changes substantially and reaches adult-like levels in early adolescence. Like many other physical and mental characteristics, the growth curve is best captured by a logistic function. These data illustrate the point that there are substantial absolute changes in specific mental functions that are associated with maturation. These data also argue that components of spatial ability are not fixed even if there is relative stability or ordering of the individuals within and across ages.

Similarly, anyone who has tested individuals in a laboratory information processing task can tell you that the ubiquitous law of practice operates. Individuals show substantial practice effects in tasks such as mental rotation. These practice effects occur within testing sessions that last an hour and over multiple testing sessions occurring on different days. However, most psychometric tests are administered in time intervals ranging from three to thirty minutes. The typical aptitude testing situation does not permit much in the way of adaptation to task and processing demands. Thus, it is not too surprising that differences in test performance, both relative and absolute remain stable over testing situations.

Typical aptitude tests tell us how an individual performs at a given point in time. Information processing analyses tell us what mechanisms are responsible for those individual differences. What tests and process analyses do not tell us is how well an individual might ultimately perform given sufficient practice, training or exposure to the cognitive performance domain. We have been exploring this issue in a series of studies that follow from our process oriented approach to the analysis of individual differences in spatial aptitude.

We will briefly describe two such studies, the first of which had several different purposes (Alderton, Pellegrino & Lydiatt, 1984). The first purpose was to examine changes in components of spatial processing as a function of practice. The second purpose was to examine such changes for high and low ability individuals in the context of two different spatial processing tasks.

One task represented spatial relations ability and the other represented spatial visualization ability. The third purpose of the study was to examine changes in reference ability scores as a function of extended practice on laboratory spatial processing tasks. Specifically, we were concerned with the effect that extended practice in spatial tasks might have on measured ability levels. The fourth major purpose of this study was to examine reference ability scores and components of spatial processing after a long delay interval.

Initially the individuals were administered a battery of reference tests assessing various spatial factors including perceptual speed, spatial relations, and spatial visualization. We then selected 36 high and 36 low ability individuals for extended testing on two processing tasks. There was an initial practice session to familiarize them with each task and they then received eight sessions of testing with four sessions on each processing task. The two tasks were mental rotation and form board solution. At the end of testing, the reference battery was re-administered. Finally, two to three months after the study was completed, many of the individuals returned for two additional sessions. The first delayed session was used to re-administer the reference test battery while the second session was used to collect performance data on the two spatial processing tasks.

Data from both tasks showed that practice leads to substantial improvement in the speed of executing specific mental processes. Figure 14 contains one such example. It shows data on the speed of mental rotation as a function of both testing session and pre-experimental measures of spatial ability. Two things are apparent. On the initial testing session there are substantial differences among individuals in the speed of rotation and the ordering of groups is consistent with the reference ability scores obtained prior to the experiment. However, the low ability individuals are capable of achieving highly speeded performance as a function of practice. Their initial inferiority relative to high ability individuals is not completely eliminated by providing practice, although they do achieve processing speeds equivalent to the levels exhibited by the highest ability individuals at the start of testing. The question then is what effect all this practice has on the performance of both high and low ability individuals when we remove them from the laboratory task situation and retest them with standard measures of spatial ability.

Figure 15 contains three panels representing performance on three different spatial factors. In each panel, pre, post and delayed test data are presented for our high and low ability groups. Data are presented as percentiles based on external norms. In the left hand panel, there is a substantial pre-test to post-test gain in performance for two different perceptual speed measures. In the center panel, the low ability individuals show substantial gains in performance for two different spatial relations measures. In the right hand panel, the low ability individuals show a substantial gain in performance for the spatial visualization measure. The performance changes exhibited in this figure far exceed normal test-retest effects and can not be attributed solely to regression toward the mean.

One might wish to assume that the effects of extended practice on reference ability measures are situation specific and ephemeral. There are three arguments against this conclusion. First, the effects observed in test score performance following extended practice were not limited to a single test. Instead, they generalized to other tests including measures of perceptual speed and other measures of spatial relations using very different types of visual stimuli. Second, the laboratory tasks are different in format and content from the reference tests they were modeled after. Perhaps the most compelling argument, however, comes from the data obtained in the two delayed testing sessions. As shown in the figure, for every reference test, performance in the delayed testing session is virtually identical to performance in the testing session following extended practice. A similar pattern of results was obtained for performance measures from the laboratory spatial processing tasks.

The data from this extended practice study can be discussed in several ways. First, they replicate previous results showing speed and accuracy differences in specific components of spatial processing. There are replicable differences between high and low ability individuals in various components of spatial processing. Second, the data indicate that many low ability individuals are capable of substantial improvement in various components of spatial information processing. By the end of four sessions of testing, we have not transformed our low ability individuals into our high ability individuals. We have, however, reduced some of the differences between ability groups. The changes in spatial processing ability are still evident after a delay of several months.

A second study illustrates an attempt to further examine the effects of extended practice on mental rotation processing parameters and psychometric indices (Regian & Pellegrino, 1984). The previous study demonstrated that practice on laboratory spatial processing tasks can influence performance on subsequently administered psychometric tests. The design of the present study permitted an investigation of the hypothesis that extended practice at mental rotation might translate to a specific pattern of enhanced performance on tests varying in content and factor identification. Previous research on mental rotation has also demonstrated practice effects for both the slope and the intercept of the rotation function. What is not clear is if either or both of these are general processing effects and/or stimulus specific processing effects. The present design permitted the discrimination of practice effects due to increased efficiency of specific processing components and practice effects due to stimulus familiarity.

Thirty-seven individuals were tested on a battery of spatial tests consisting of two perceptual speed tasks, two spatial relations tasks, and one spatial visualization task. They were then given five sessions of mental rotation practice followed by a readministration of the spatial test battery. The sessions varied with respect to the presence or absence of specific sets of "equivalent" stimuli. Stimulus set X was presented in all five sessions and provides a baseline for comparing practice effects. Stimulus set Y occurred in sessions one, two, and five, while stimulus set Z occurred in sessions three, four, and five. As individuals became increasingly practiced at mental rotation it was possible to compare stimulus sets with varying degrees of familiarity to observe general and item specific effects. Session three provides key comparisons of interest since individuals were highly familiar with one set of stimuli but unfamiliar with the other set of stimuli. In all sessions, the stimulus sets were not separated but were randomly intermingled. All stimuli consisted of random polygons similar to those found on the Cards Rotation Test (see Figure 2).

Figure 16 shows that practice related changes in the intercept of the rotation function were substantial and primarily complete by session three. In addition, these effects fully generalized to the new stimulus set. Figure 16 shows that changes in the slope were also substantial and continued over the course of the experiment. More importantly, these effects did not generalize to the new stimulus set in session three. The slope for the unfamiliar stimulus set in session three was equivalent to the slope for the stimulus sets in session one. Thus, the intercept reduction was independent of stimulus familiarity while the slope reduction was not. Figure 17 shows that both of these practice effect patterns were present for high and low ability individuals. In addition, the figure shows that ability differences exist for both components of processing at the beginning of practice and are reduced by the end of practice.

As in our previous study, practice had an impact on psychometric indices, with individuals showing systematic increases on all five tests. These increases were far beyond what would be expected in a test-retest situation without intervening practice. Since each test is scaled differently, it is useful to express the pretest to posttest changes in a standardized format. By dividing each absolute change by the maximum possible change we obtain the percent increase in performance relative to the maximum possible. Of the two perceptual speed tests, there was a mean increase of 54% on the Identical Pictures test and 37% on the perceptual speed test comparing alphanumeric strings. We expected a higher increase for the identical pictures test since it measures the speed of matching stimuli that are more similar in content to the practice task. Of the two spatial relations tasks, there was a mean increase of 52% on the Cards Rotation Test and 42% on the Primary Mental Abilities space test. Again, the stimuli for the cards test are more similar to the stimuli in the practice study than are the stimuli from the PMA space test. The spatial visualization task showed an increase of 28%. A smaller increase on this task would be expected since spatial visualization tasks involve processing components of perceptual speed and spatial relations tasks, but also require higher order processing components as well. Finally, we should note that in most cases, low ability individuals achieved performance on the posttest comparable to high ability individuals on the corresponding pretest.

Conclusions

We think that our data on the relationships among practice effects, ability levels and test scores provide a strong argument for the need to combine psychometric, information processing, and developmental or learning approaches to the study of intellectual ability. Certainly, the data indicate that ability differences manifest on standard reference tests are interpretable in terms of theories and models of spatial information processing. However, our data on practice effects, as well as developmental data, also seem to argue that differences obtained in a five to 25 minute testing session are not the whole picture with respect to an individual's abilities in the spatial domain. Like many other cognitive activities, spatial processing is subject to substantial developmental change and practice effects. Our low ability individuals show this to be the case. What we have not shown are data on individual subjects. These data reveal that the practice effects obtained in the experimental tasks and the score changes on the reference tests are highly variable over individuals. Some low ability individuals show substantial improvements in spatial processing while others do not. Typical testing procedures are incapable of detecting such differences and provide little or no information about the level of performance or skill that an individual could achieve.

Implications for Assessment

Questions about intellectual ability, including the development of a comprehensive theory of intellectual ability can be better pursued when psychometric, information processing, and developmental approaches are integrated. We have tried to illustrate this by reviewing efforts of this type focusing on spatial cognition. Similar illustrations could be provided for other areas of cognition such as verbal ability and reasoning. For many years, psychometricians have known about individual differences in spatial cognition and they have developed many instruments that assess this aspect of intellectual ability. These instruments predict performance in certain academic and technical courses. By linking information processing theories and methods of analysis with psychometric data we have begun to better understand individual differences in spatial ability. By introducing an individual differences approach into information processing theory we have also begun to tap a powerful method for testing certain basic assumptions of this theoretical perspective. More specifically, individual differences are what Underwood (1975) termed "a crucible in theory construction" providing tests of assumptions such as separability of processes and process invariance over situations. By combining information processing and developmental or learning approaches we can better understand the qualitative and quantitative performance changes that occur with development, experience, and practice. Such a combination of perspectives also enhances our understanding of the evolution of cognitive structures, processes, and knowledge. All of the preceding represent enhancements to theory.

There are also benefits to be gained relative to the technology of ability assessment. Elsewhere, it has been argued that modern computer technology, in combination with extant psychometric procedures and information processing models, can contribute to new forms of ability assessment (Hunt & Pellegrino, 1985). This can come about in two general ways. The first is by permitting a more refined measurement of performance for tasks and factors currently in use. The second is by permitting the measurement of performance on tasks that it would be impossible to present without modern technology.

In the first case, enhanced assessment is accomplished by breaking down performance on perceptual speed, spatial relations, or spatial visualization tasks into sets of measures reflecting cognitive processes and capacities.

Rather than just an overall performance score, we also derive measures of encoding speed, rotation speed, transformation accuracy, etc. The tasks and measures used come from existing tests and theories. At present, it is possible to construct a battery of computer administered tasks preserving the general factor structure we have referred to throughout this paper while at the same time providing detailed diagnostic information about specific cognitive functions. To do so would require two things: (1) systematic problem sets like those used in process analyses of individual differences, and (2) computers for the presentation of problems and the monitoring of response latency and accuracy. This can be done now for many perceptual-spatial processing components by simply drawing upon information processing studies such as those described earlier. We could also enhance such a battery by including tasks that do not currently appear in paper and pencil batteries but which assess certain imagery and spatial functions postulated in Kosslyn's theory. Some of the tasks could be drawn from the work of Kosslyn et al. (1983) and Poltrock and Brown (1984). It should be noted that one contribution of information processing research to the construction of such an assessment battery is a framework and method for decomposition of existing measures while a second contribution is the generation of new tasks and measures. All of the foregoing deal with the processing of static displays and stimuli.

The second case that must be considered with respect to spatial cognition is the processing of dynamic rather than static spatial relations. Our intuitive sense of "spatial ability" is that it extends beyond dealing with static images and is frequently exercised in a world of objects moving in relation to each other and individuals moving in relation to objects. Given two or more objects on a display moving with a certain speed and on a certain trajectory, how well can we predict and infer what will happen? Will they collide? Which one will reach a certain point first? When will an object reach a certain point? The processing of dynamic spatial relations is of interest both in terms of psychological theories of spatial cognition and in terms of the psychometric assessment of human spatial abilities. There is just as much reason to assume that no relation exists between current spatial ability tests and tests of dynamic spatial reasoning as there is to assume that some relation exists. Computer technology permits the development, implementation and evaluation of dynamic spatial reasoning tasks that are otherwise not possible. Such tasks might constitute an important part of the assessment of spatial ability. Should we just go ahead and develop such tasks or should we do so within a theoretical context? Asked in another way, do we want to do more than just simply report correlations between new instruments and old ones? We believe that the answer is obvious. The solution is to develop tasks and analyze relationships within an information processing framework. By doing so we can enhance both theory and practice at the same time.

We need to consider the benefits of such modified assessment in light of another practical issue, one that has been at the center of much controversy. The issue concerns the goals and purposes of assessing intellectual ability and the uses of mental tests. For some time there has been consensus among psychometricians that the predictive level of mental tests is probably about as high as one can expect to achieve, given the typical constraints of the testing situation. The historical emphasis on predictability stems from two sources, the first being the use of tests for selection purposes. Implicit in this use, however, is a view that intelligence in relatively stable and inert. That is, the assumption underlying traditional mental testing is that some mental entity, call it g, or Gc, Gf, or Gv, or v:ed or k:m, determines success in school and similar intellectual endeavors. By measuring this accurately, one can then predict a person's success in such endeavors. From cognitive and developmental perspectives it seems more reasonable to start with the point of view that intellectual skills are malleable rather than fixed. With a malleable intelligence as the starting point, the predictive value of tests is no longer a prime concern. If we believe that intelligence is malleable, then what educators need to know are those experiences that will be most likely to assist a student to achieve particular educational goals. Believing that intelligence is malleable, the value of tests lies in their ability to provide some of the information needed to design instruction appropriate for an individual. Thus, the important criterion for evaluating a test becomes its diagnostic value. Mental tests derived from the psychometric tradition are not terribly useful in this regard. The outcome of almost any mental test is a score that simply indicates a person's standing relative to a normative sample. However, such information is insufficient for the design of appropriate instruction. In this regard, mental tests are not unlike a thermometer as a measure of physical health. They provide a rough index as to whether a person is healthy or not but provide precious little in the way of specific diagnostic information. One could hope then that by combining the focus on process exemplified in information processing and developmental approaches with existing psychometric measures, it would be possible to devise instruments and testing situations that, although they may be no more predictive than their predecessors, will provide more extensive diagnostic information regarding an individual's cognitive assets and liabilities. This would include testing situations sufficiently extended so that changes in performance could be observed, including the capacity to adapt to novel situations and automate performance (Sternberg, 1984).

In summary, whether considering practical issues of the uses and misuses of tests or the more theoretical facets of intelligence and intellectual ability, the conclusion is much the same. Psychometric theory and practice, though it has long held center stage, is not sufficient to address the theoretical and applied issues associated with intellectual ability. Information processing theory is a relative newcomer and it alone or in combination with developmental theory is also insufficient to address these issues. An integration of perspectives and disciplines is needed to achieve progress in tackling many of the theoretical and pragmatic issues associated with the construct of intellectual ability.

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Figure Captions

1. Perceptual Speed sample items. From top to bottom: Identical Pictures (find the matching picture), Number Comparison (mark the mismatching pairs), Finding A's (cross out words containing a's). From Ekstrom, French & Harman (1976).

2. Spatial Relations sample items. From top to bottom: Flags (Thurstone, 1938), Aerial Orientation (Guilford & Lacey, 1947), PMA Space (Thurstone, 1965), Cards Rotation (Ekstrom, French & Harman, 1976), Cubes Comparison (Ekstrom, French & Harman, 1976). To solve, indicate if the same side of the figures are shown or if the two figures are consistent (Cubes).

3. Spatial Orientation sample items. From top to bottom: Spatial Orientation (match the left cockpit view with the correct distant scene), Hands (indicate Right or Left for each), Reconnaissance (match the lower cockpit view with the reconnaissance view letter). From Guilford & Lacey, 1947.

4. Visualization sample items. From top to bottom: Minnesota Paper Form Board (find the correct complete puzzle; Likert & Quasha, 1970), Visualization of Maneuvers C (find the correct new position; Guilford & Lacey, 1947), Punched Holes (find the correct unfolded paper; Ekstrom, French & Harman, 1976), Surface Development (match the numbers with the letters on the right; Ekstrom, French & Harman, 1976), DAT Space (find the completed figure; Bennett, Seashore & Wesman, 1974).

5. Schematic of factor relationships as a function of speededness/difficulty and complexity: Perceptual Speed (PS), Spatial Relations (SR), Spatial Orientation (SO) and Visualization (VZ).

6. Structural equation model decomposing spatial visualization ability into cognitive components. Poltrock & Brown (1984; p. 132).

7. Ability differences in latency parameters of mental rotation.

8. Prototypical latency data for simple versus complex mental rotation. From Pellegrino & Glaser (1979).

9. Ability differences in parameters of complex mental rotation separately for same and different judgments. Key: TQ is Top Quartile, LQ is Lower Quartile.

10. Experimental Form Board problem types. From Mumaw & Pellegrino (in press).

11. Ability differences in Form Board performance. From Mumaw & Pellegrino (in press).

12. Ability differences in Surface Development performance.

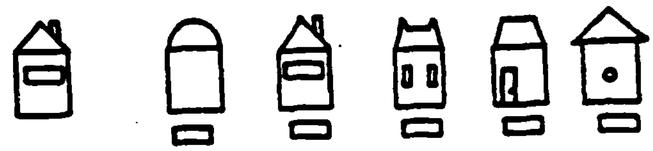
13. Developmental changes in rate of mental rotation. From Kail (1983).

14. Practice effects in the rate of mental rotation separately for PMA Space test raw score groups.

15. Test score changes following extended practice separately for high and low ability groups.

16. Average practice effects in parameters of mental rotation for different stimulus sets.

17. Ability differences in practice effects for parameters of mental rotation. Filed symbols for low ability.



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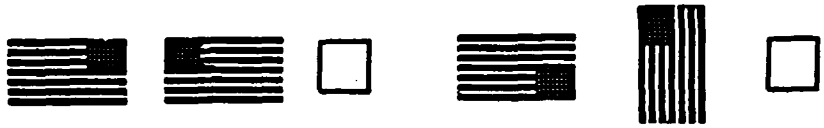
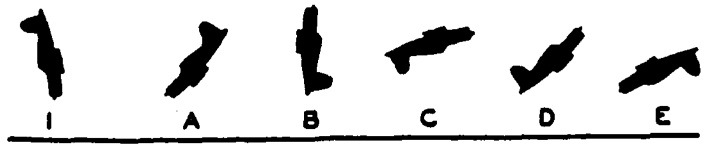
11653	____	11652	6430017	____	6430017
617439428	____	617439428	518198045	____	518168045
1860439	____	1860439	55179	____	55097
90776105	____	90716105	63216067	____	63216057

Cross out words containing an 'a'.

picnic	other	person
smart	straw	warm
finger	noisy	juice
useful	defer	enter
slowly	field	ordeal
meant	mend	nurse
quick	skill	cool

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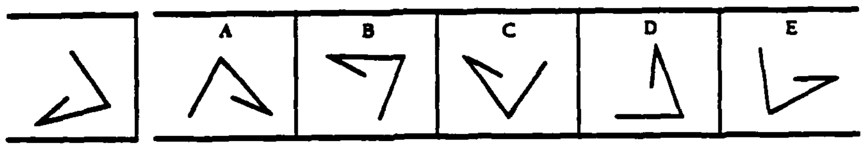
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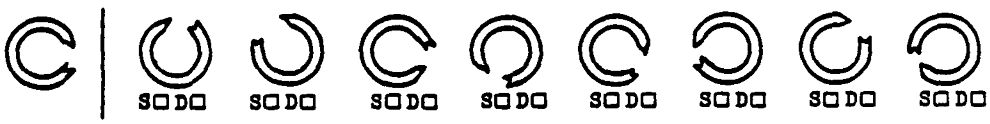
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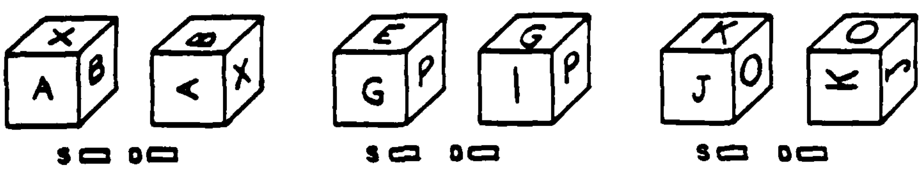
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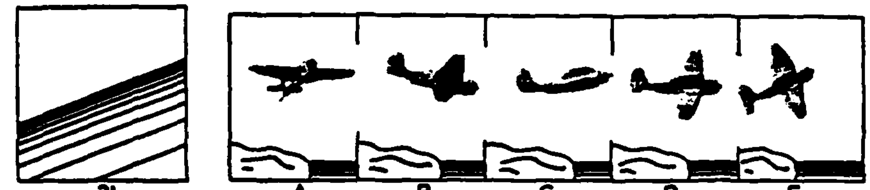
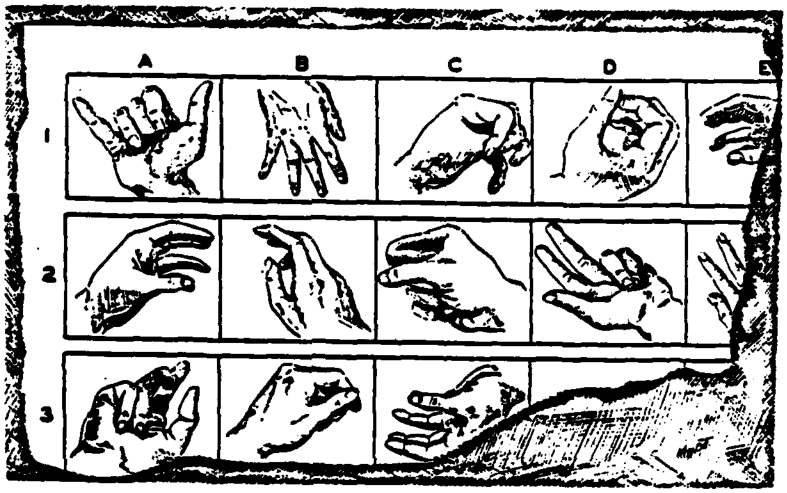
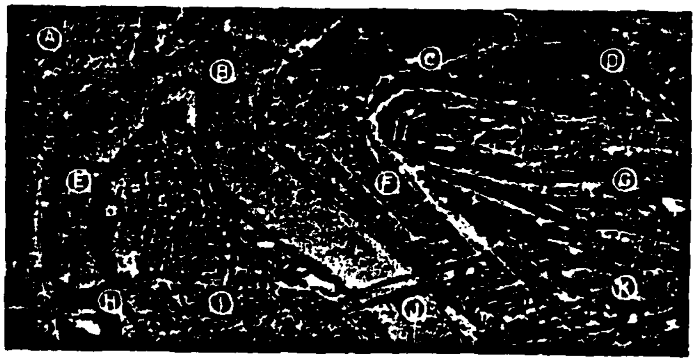


31 A B C D E





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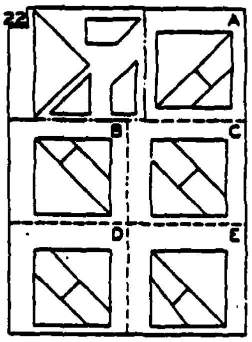
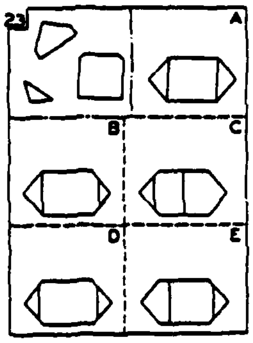
1


22
A
B
C
D
E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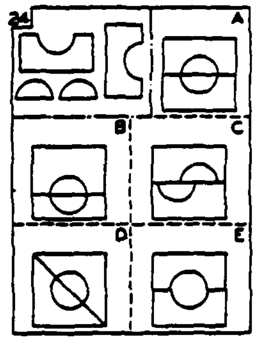
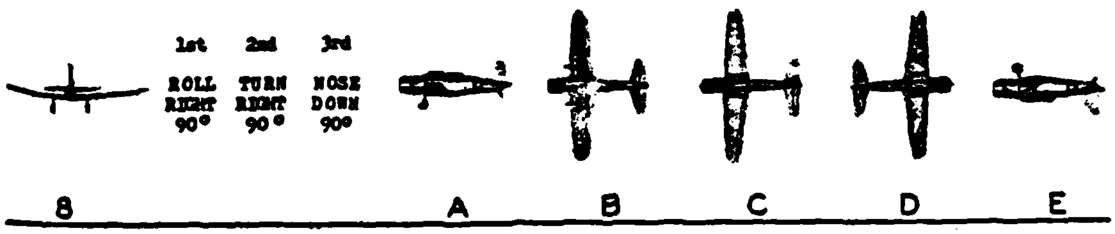
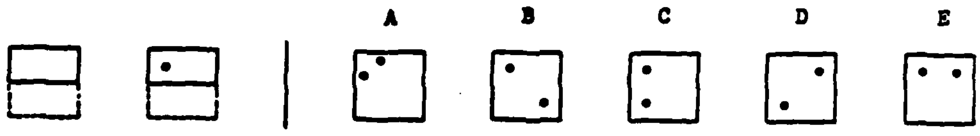
A
B
C
D
E


24
A
B
C
D
E


1st
ROLL
RIGHT
90°
2nd
TURN
RIGHT
90°
3rd
NOSE
DOWN
90°
8
A
B
C
D
E


A
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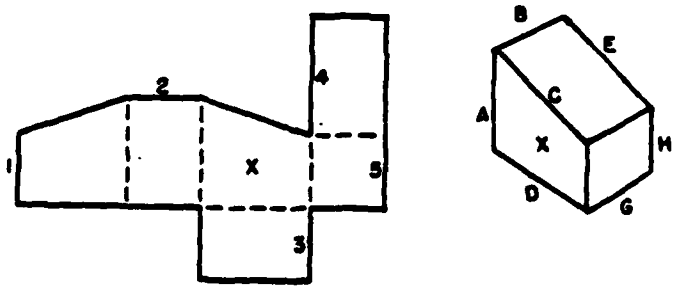
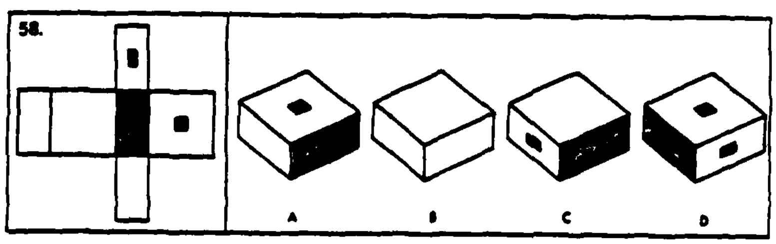
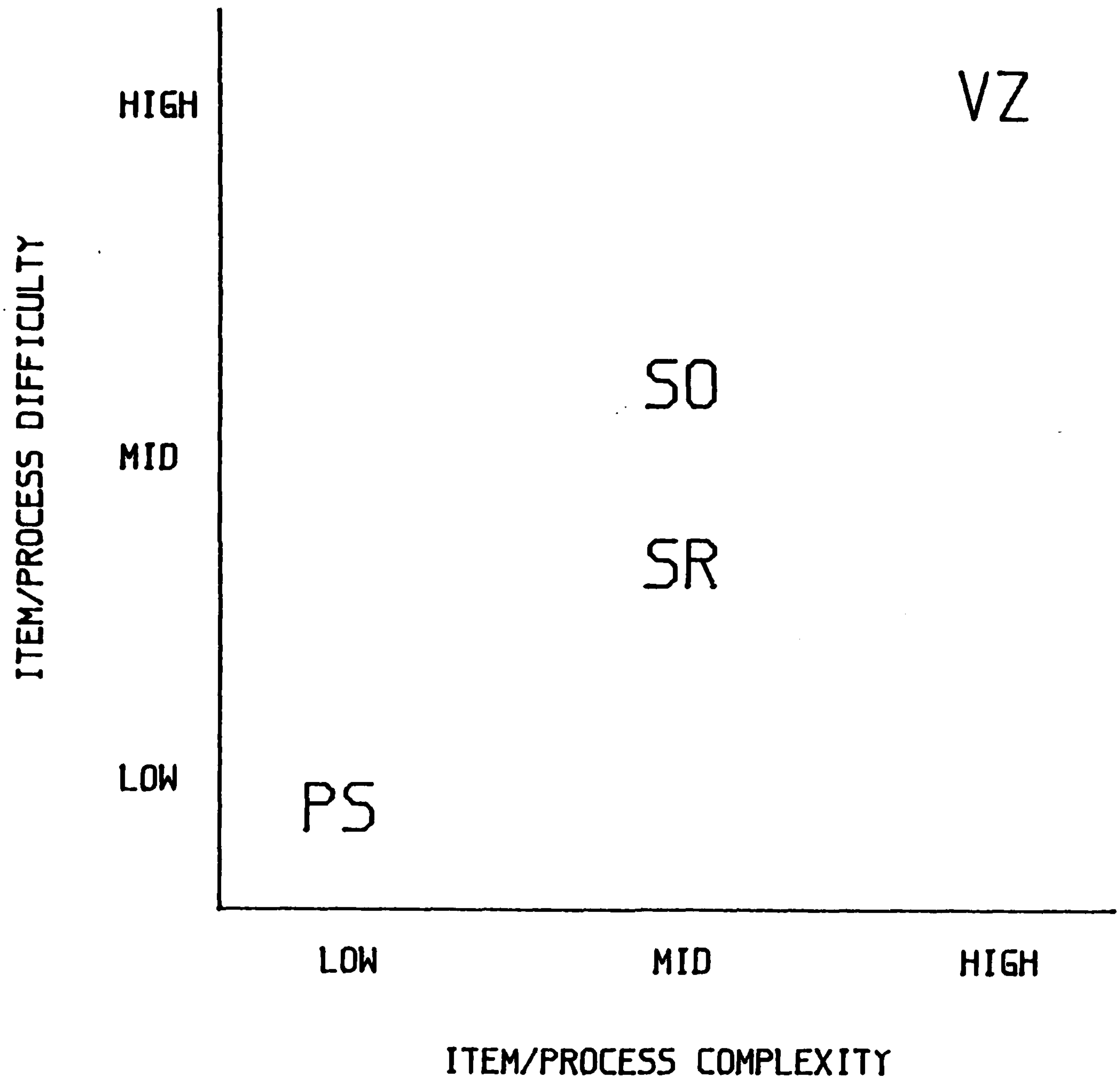
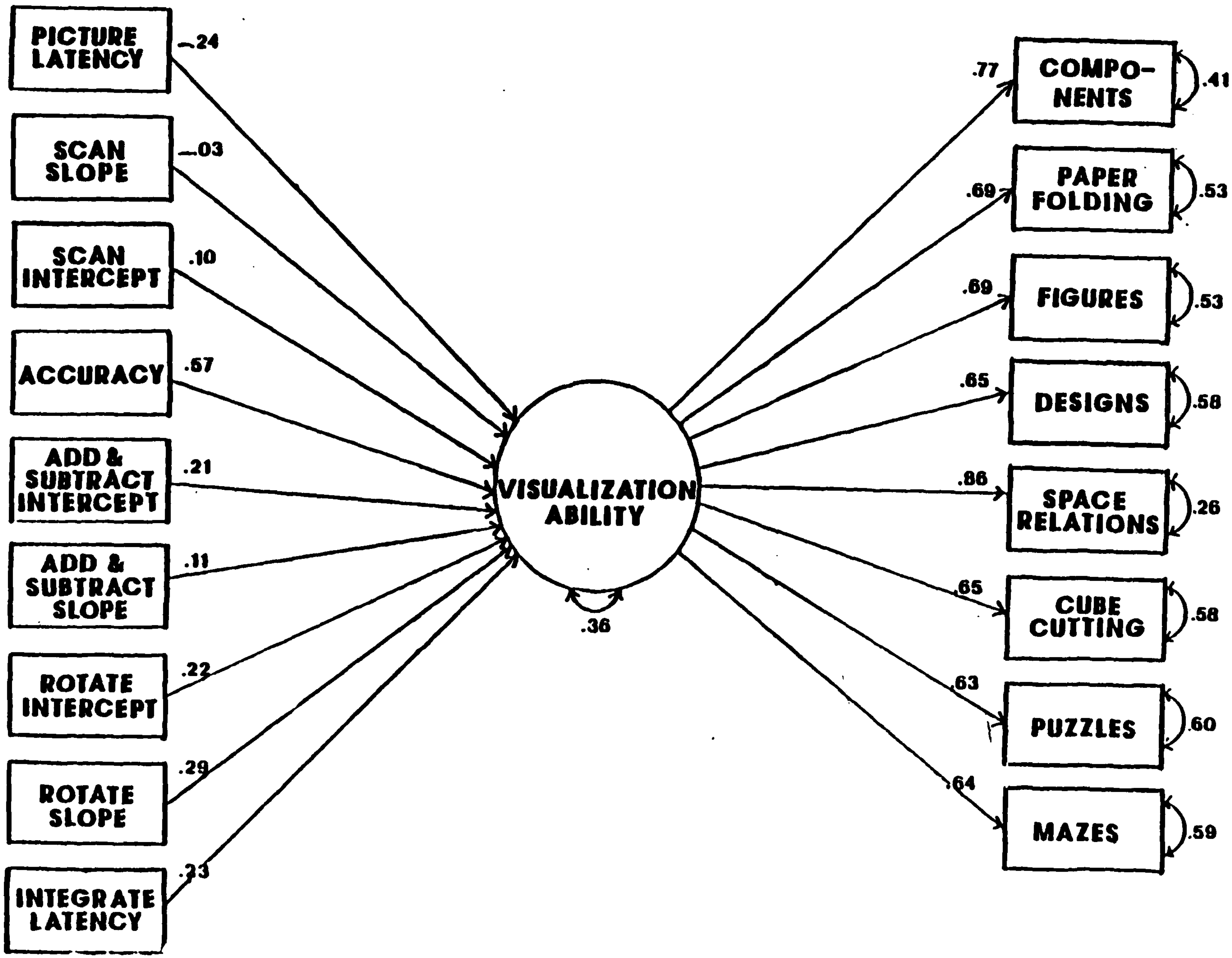
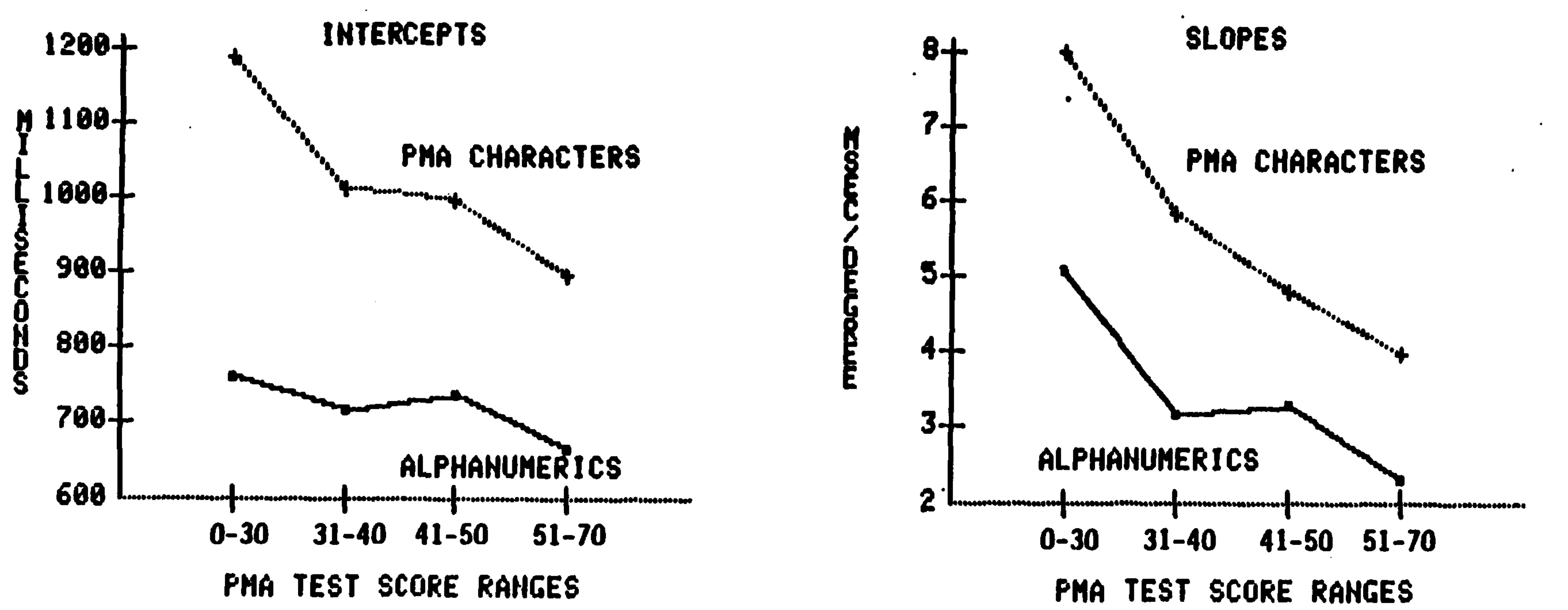
C
D
E


1
2
X
4
5
3
B
E
C
A
X
H
D
G

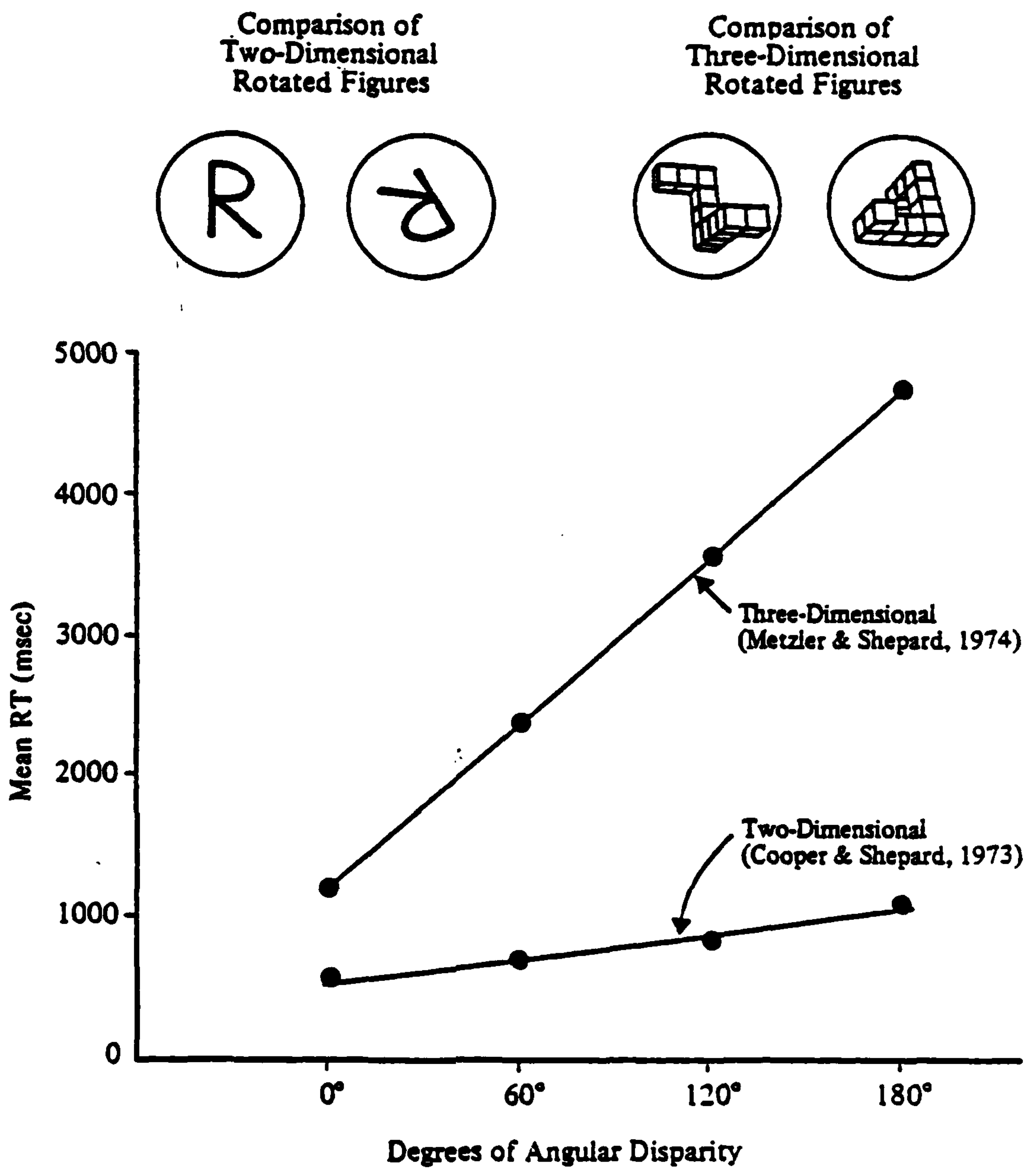

58.
A
B
C
D

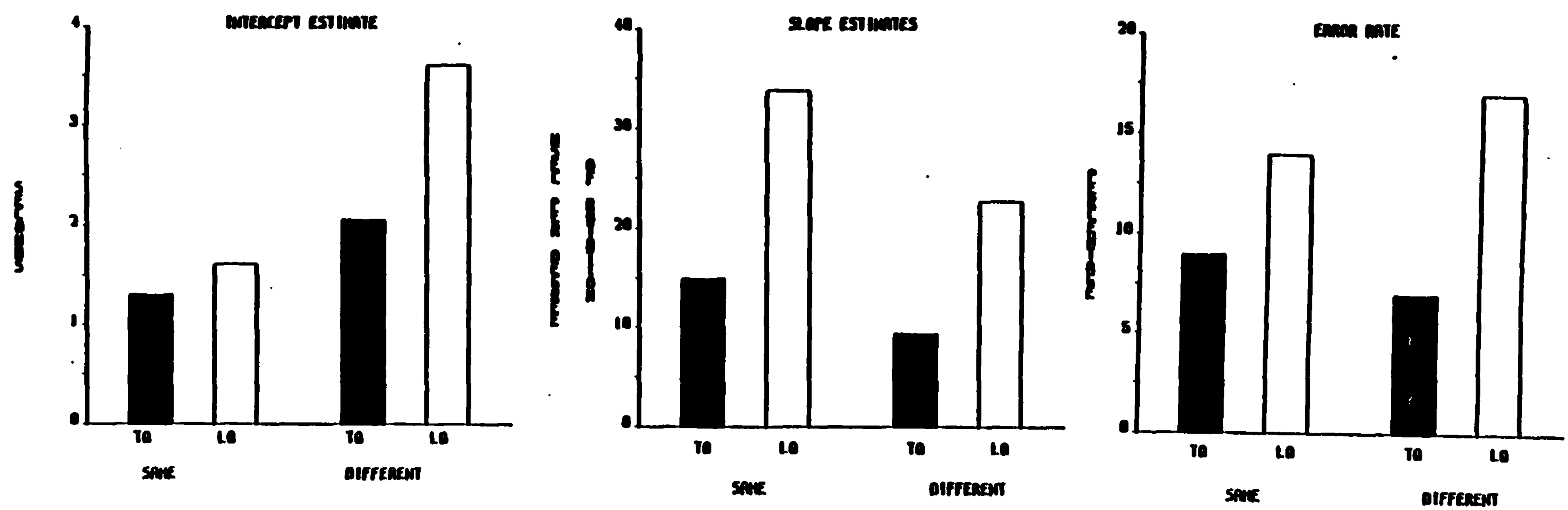

ITEM/PROCESS DIFFICULTY
HIGH
MID
LOW
VZ
SO
SR
PS
LOW
MID
HIGH
ITEM/PROCESS COMPLEXITY


PICTURE LATENCY
—.24
SCAN SLOPE
—.03
SCAN INTERCEPT
.10
ACCURACY
.57
ADD & SUBTRACT INTERCEPT
.21
ADD & SUBTRACT SLOPE
.11
ROTATE INTERCEPT
.22
ROTATE SLOPE
.29
INTEGRATE LATENCY
.33
VISUALIZATION ABILITY
.36
.77
COMPO-NENTS
.41
.69
PAPER FOLDING
.53
.69
FIGURES
.53
.65
DESIGNS
.58
.86
SPACE RELATIONS
.26
.65
CUBE CUTTING
.58
.63
PUZZLES
.60
.64
MAZES
.59



INTERCEPTS
MILLISECONDS
1200
1100
1000
900
800
700
600
PMA CHARACTERS
ALPHANUMERICS
0-30
31-40
41-50
51-70
PMA TEST SCORE RANGES
SLOPES
MSEC/DEGREE
8
7
6
5
4
3
2
PMA CHARACTERS
ALPHANUMERICS
0-30
31-40
41-50
51-70
PMA TEST SCORE RANGES


Comparison of Two-Dimensional Rotated Figures
Comparison of Three-Dimensional Rotated Figures
R
5000
4000
3000
2000
1000
0
Mean RT (msec)
Three-Dimensional (Metzler & Shepard, 1974)
Two-Dimensional (Cooper & Shepard, 1973)
0°
60°
120°
180°
Degrees of Angular Disparity



INTERCEPT ESTIMATE
0
1
2
3
4
TO
LO
TO
LO
SAME
DIFFERENT
SLOPE ESTIMATES
0
10
20
30
40
TO
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DIFFERENT
ERROR RATE
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5
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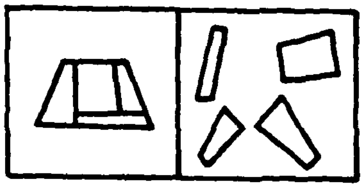
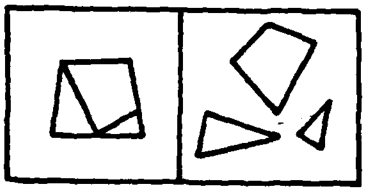
15
20
TO
LO
TO
LO
SAME
DIFFERENT



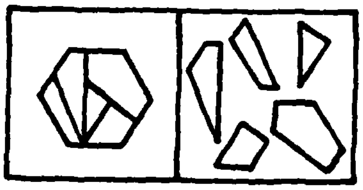
Rotated & Displaced

Encoding, Search, Rotation, Comparison, Response



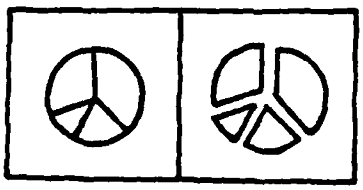
Rotated

Encoding, (Search), Rotation, Comparison, Respons



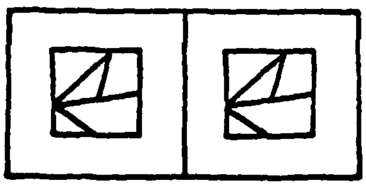
Displaced

Encoding, Search, Comparison, Response



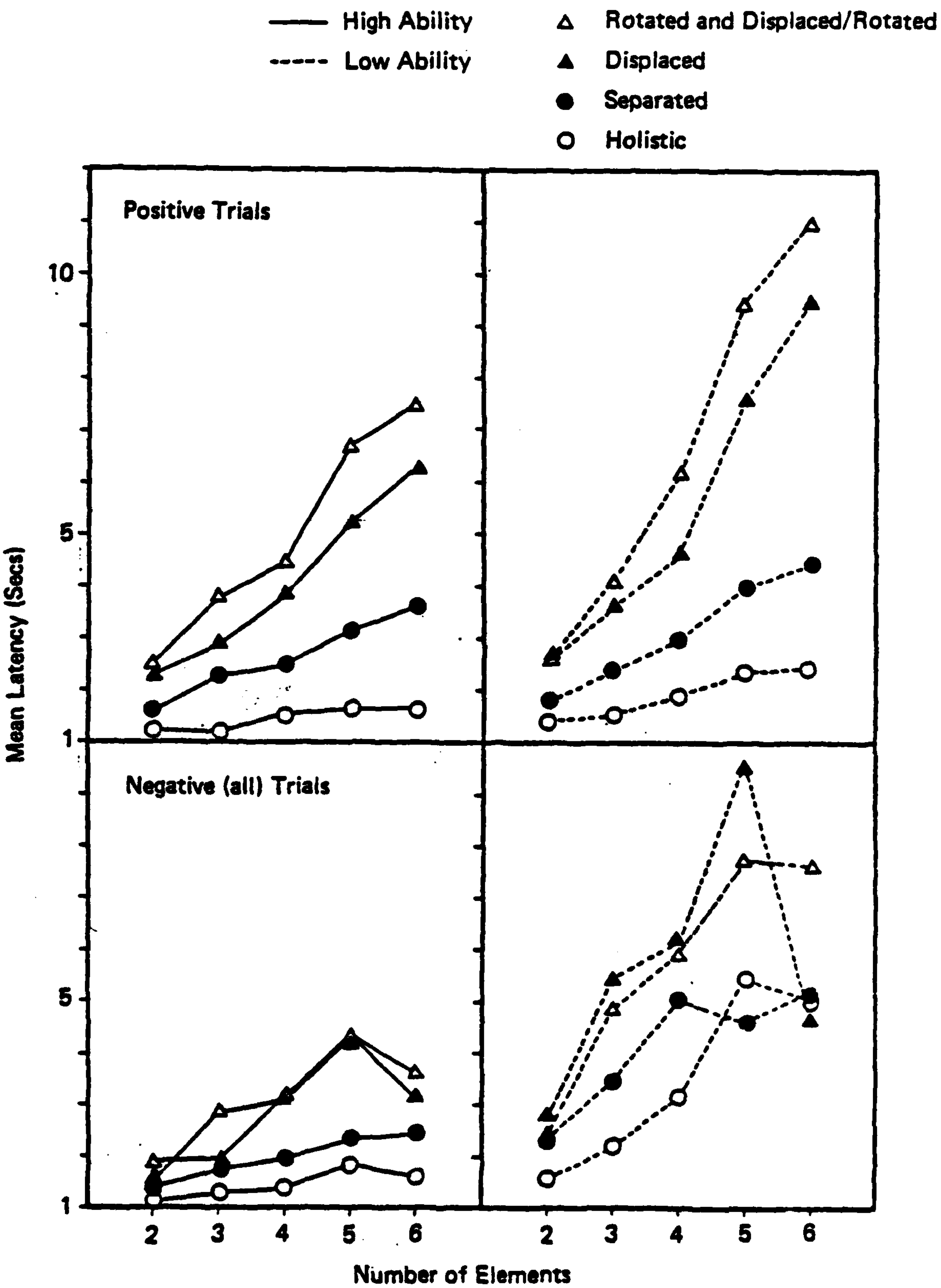
Separated

Encoding, Comparison, Response

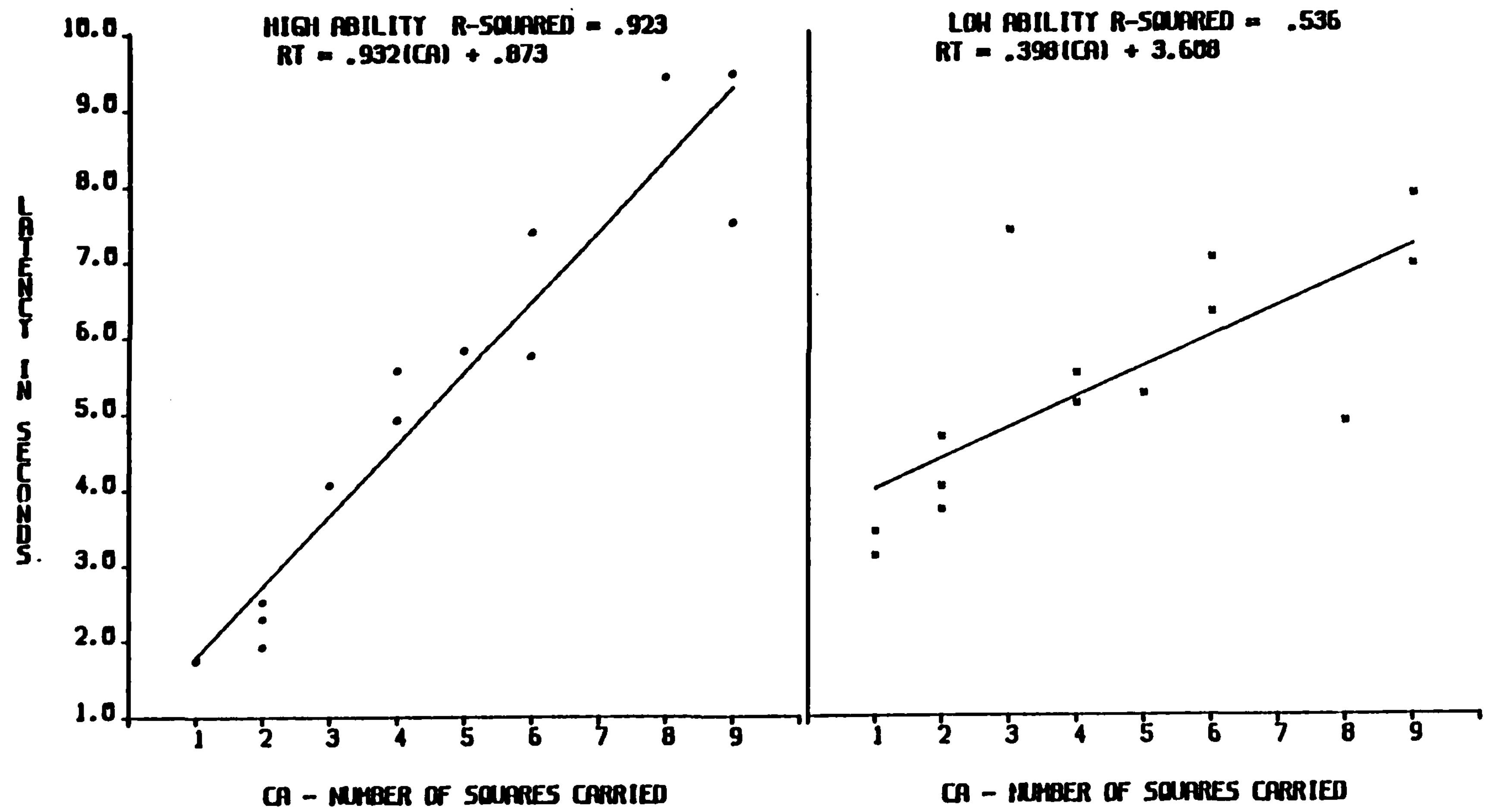


Wholistic

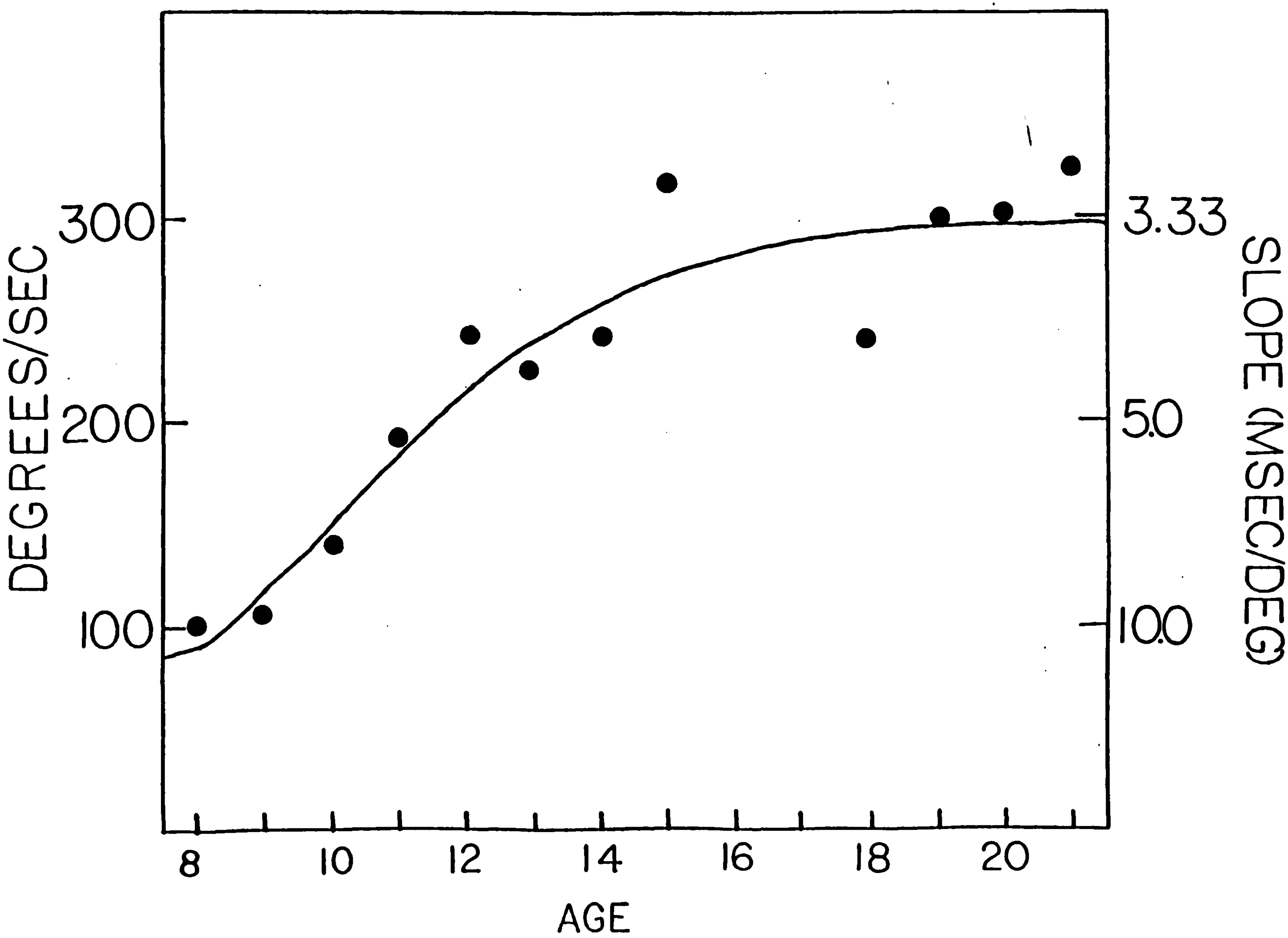
Encoding, Comparison, Response

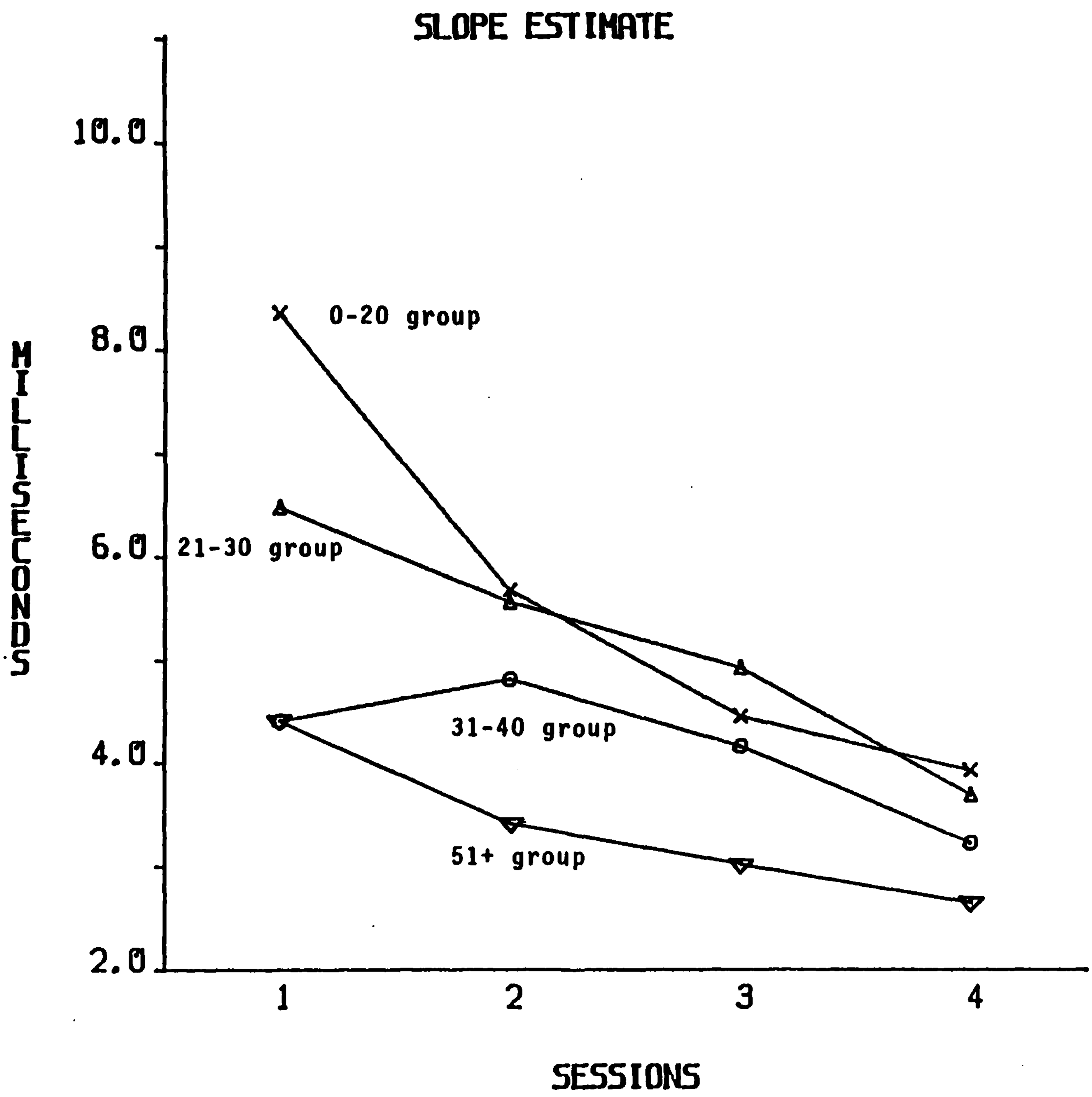


High Ability
Low Ability
Rotated and Displaced/Rotated
Displaced
Separated
Holistic
Positive Trials
Negative (all) Trials
Mean Latency (Secs)
10
5
1
5
1
2
3
4
5
6
2
3
4
5
6
Number of Elements

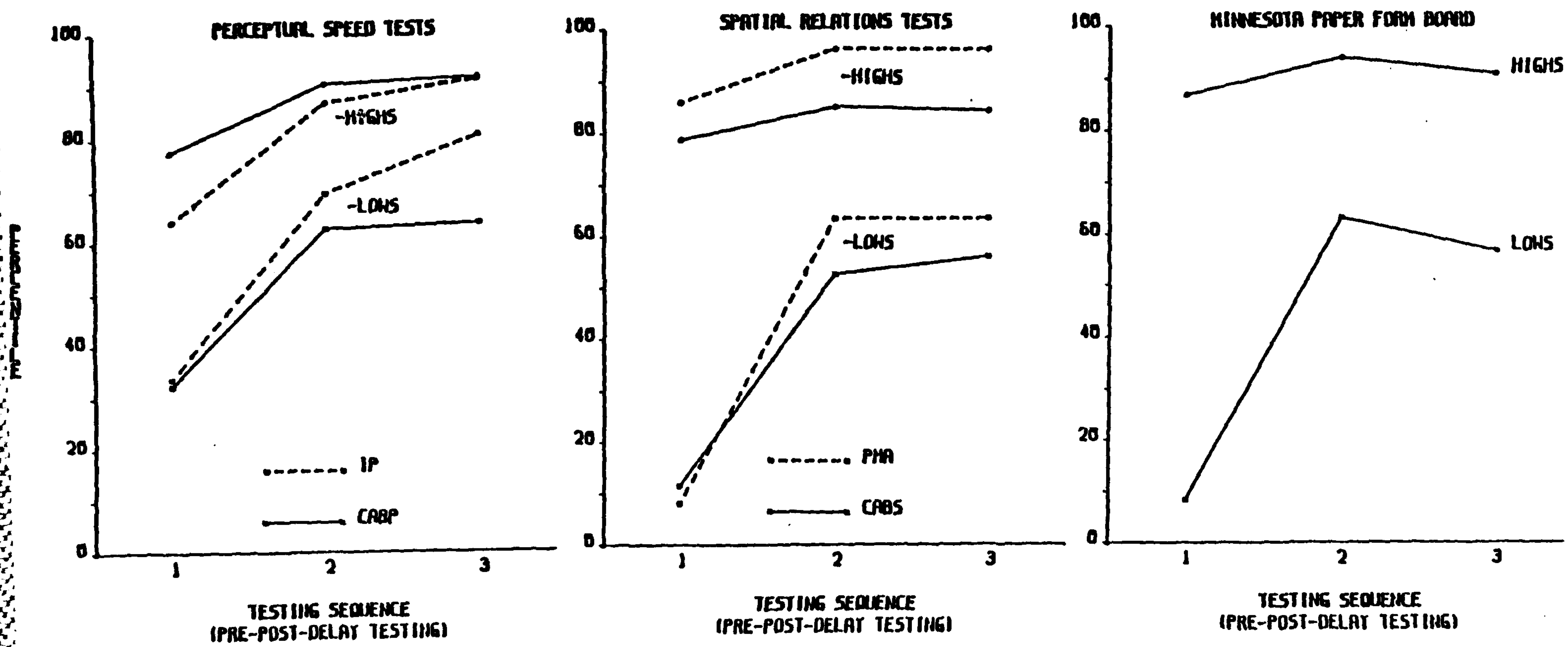


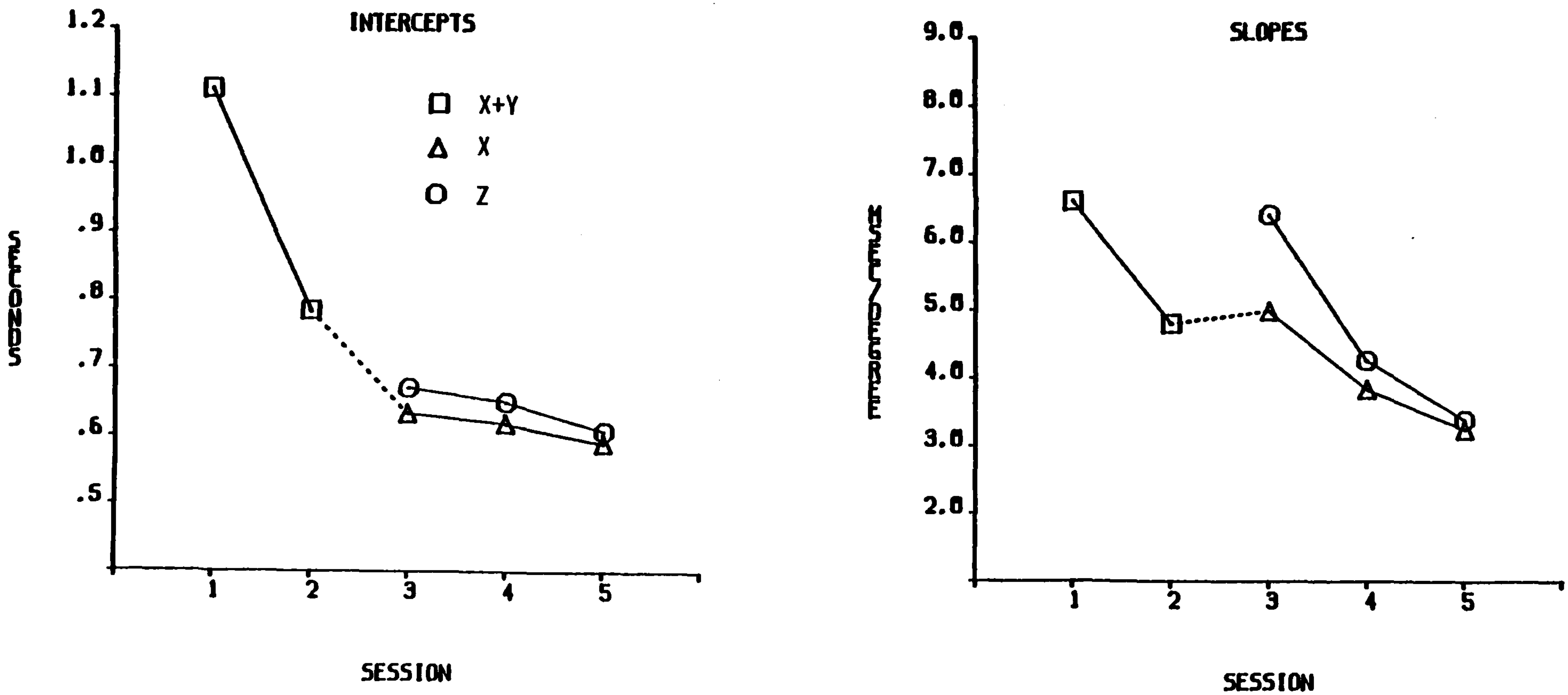
HIGH ABILITY R-SQUARED = .923
RT = .932(CA) + .873
LOW ABILITY R-SQUARED = .536
RT = .398(CA) + 3.608
LATENCY IN SECONDS
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
1 2 3 4 5 6 7 8 9
CA - NUMBER OF SQUARES CARRIED
CA - NUMBER OF SQUARES CARRIED

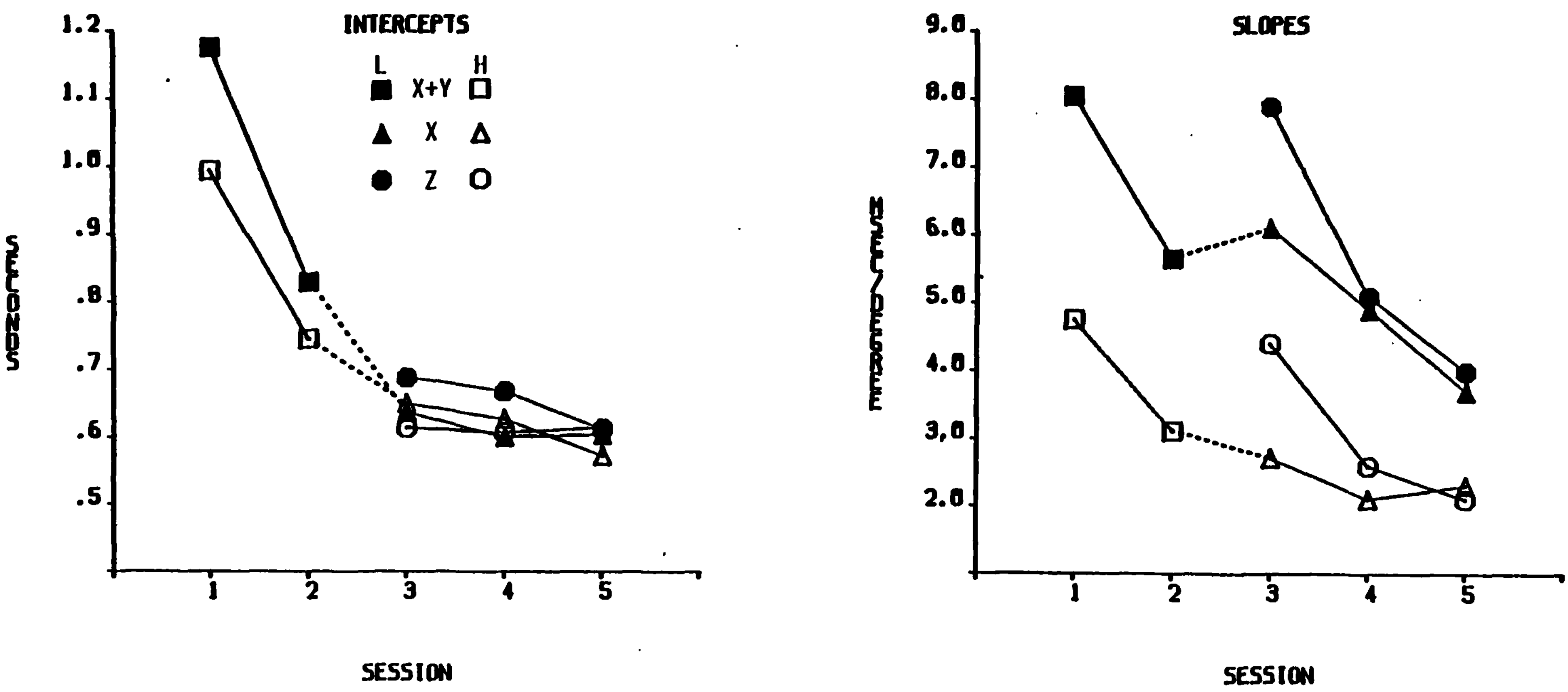

DEGREES/SEC
300
200
100
SLOPE (MSEC/DEG)
3.33
5.0
10.0
8
10
12
14
16
18
20
AGE



SLOPE ESTIMATE
MILLISECONDS
10.0
8.0
6.0
4.0
2.0
0-20 group
21-30 group
31-40 group
51+ group
1
2
3
4
SESSIONS


PERCENTILE
PERCEPTUAL SPEED TESTS
-HIGHS
-LOWS
IP
CABP
TESTING SEQUENCE
(PRE-POST-DELAY TESTING)
SPATIAL RELATIONS TESTS
-HIGHS
-LOWS
PMA
CABS
TESTING SEQUENCE
(PRE-POST-DELAY TESTING)
MINNESOTA PAPER FORM BOARD
HIGHS
LOWS
TESTING SEQUENCE
(PRE-POST-DELAY TESTING)


INTERCEPTS
X+Y
X
Z
SECONDS
1.2
1.1
1.0
.9
.8
.7
.6
.5
1
2
3
4
5
SESSION
SLOPES
MSEC/DEGREE
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1
2
3
4
5
SESSION


INTERCEPTS
L
H
X+Y
X
Z
SECONDS
1.2
1.1
1.0
.9
.8
.7
.6
.5
1
2
3
4
5
SESSION
SLOPES
MSEC/DEGREE
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
SESSION

DTIC
END
4-86